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Life Cycle Analysis of a Particleboard Based on Cardoon and Starch/Chitosan

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Abstract: This work analyzes the life cycle environmental impacts of producing a particleboard based on cardoon fibers and a starch/chitosan adhesive from a "cradle-to-gate" perspective, considering the following life cycle steps: raw material production, adhesive preparation (component mixing and heating), cardoon fiber preparation (crushing and sieving), adhesive and fiber mixing, hot-pressing and final processing. The functional unit is a particleboard with the dimensions of 220 × 220 × 16 mm^3. For the life cycle inventory, experimental data obtained from the production of particleboard on a pilot scale were used. The Aspen Plus V9 software was used to simulate the heating process in the manufacture of the biological adhesive and obtain the data associated with this stage. Portuguese or European conditions were considered for the background processes, using data from the EcoInvent V3.5 LCI database. The environmental impacts were quantified using the RECIPE methodology. To complement the study, the VOCs present in the panel were analyzed using the "active headspace" technique. The results show that for most of the environmental impact categories, energy consumption is dominant, followed by starch and chitosan production. Using fully renewable electricity produced in photovoltaic panels, instead of the Portuguese electricity mix, significantly reduces the impacts in most of the environmental impact categories, for example, the carbon footprint is reduced by 34%. Future studies will analyze how the environmental impacts can be further reduced, and how process scale-up may influence them.

Keywords: bio-based materials; cardoon; circular economy; life cycle thinking; particleboards

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1. Introduction

The global economy has been considered too resource-intensive, consuming almost twice what the Earth can regenerate each year [1]. The transition to renewable resources and materials is a fundamental strategy to contribute to the sustainability of the current production systems, which depends on several factors, including the entire life cycle of products, waste management and resource efficiency. Although with some limitations, it is possible to use renewable materials from various sources, including agricultural, marine and forest biomass and bio-waste to create sustainable products and materials [2–4]. However, the responsible and efficient management of renewable materials is crucial for ensuring their long-term sustainability and maintaining capacity for the growth and renewal of these resources [2]. This approach aligns with the principles of sustainable resource management and the broader goal of achieving a circular economy, where resources are used efficiently, waste is minimized, and ecosystems are preserved [5]. The aim should be to use all the biomass produced in a sustainable way, minimizing the production of waste, while cascading it to produce different goods for human use [6]. It is also important to ensure that biomaterials are used in applications with a high potential for circular production and consumption, promoting sustainability and minimizing environmental impact. Circular applications of biomaterials are those that are designed to maximize resource efficiency [7].

A particleboard is a versatile engineered wood-based panel made from wood particles, such as wood chips, sawmill shavings, and sawdust, that are bonded together with adhesive resins under pressure and heat [8]. The densities of these boards are usually in the range of 600 to 750 kg/m^3, while boards with densities below 600 kg/m^3 are referred to as lightweight boards [9]. There are different methodologies to achieve a lightweight particleboard, such as: uses of lightweight wood species, sandwich panels with a foam core (e.g., of polyurethane or polystyrene foam, cardboard-based honeycomb core, less compaction of the wood, and production of extruded particleboard containing longitudinal tubular hollow spaces). Within the construction universe, lightweight particleboard panels are widely used in the woodworking and carpentry industry, because the low weight reduces the costs associated with transportation and assembly, as well as relieves the weight of the construction. However, it is necessary to take into consideration that a reduction of its density may have a negative impact on the panel's mechanical performance.

The affordable price, durability and ease of use make particleboard a popular choice for construction and furniture applications, such as [3] flooring underlayment, partitions and wall paneling, insulating layer in roofing systems, furniture manufacturing, among others. They offer versatility in design and can be easily shaped and finished to match different architectural styles, and have several advantages, including cost-effectiveness, dimensional stability, and ease of installation. However, it is important to note that particleboards may have limitations in terms of moisture resistance and load bearing capacity compared to other materials like plywood or solid wood [10,11].

Particleboards are typically produced using polymeric resins derived from non-renewable resources such as fossil fuels, many of which contain formaldehyde in combination with urea, melamin, or phenol as a raw material, due to its good adhesive performance, high reactivity and lower price [12]. The two most commonly used resins in particleboard production are urea–formaldehyde (UF) and phenol–formaldehyde resins (PF). These resins provide the adhesive properties necessary to bind the wood particles together during the manufacturing process. The extraction and processing of these resources can have significant environmental and energy-related impacts, such as contributing to greenhouse gas emissions and resource consumption. Also, UF and PF resins can release formaldehyde, and other volatile organic compounds (VOCs) as phenol, into the indoor air [12]. Formaldehyde and phenol emissions from particleboard can have health implications and contribute to indoor air pollution. Formaldehyde is a carcinogenic compound, suspected of being mutagenic and skin sensitizing. Phenol is suspected of being mutagenic. Moreover, the production process may generate waste materials and byproducts, some of which may need to be disposed of or treated. To address these environmental concerns and move toward more sustainable particleboard production, there has been a push to develop alternative resin systems and more eco-friendly manufacturing processes, using renewable resources, while ensuring that the environmental impacts linked to its production are reduced [4].

The development of particleboards manufactured using renewable resources and minimizing environmental impacts is an important goal in sustainable construction practices [4]. Agricultural residues are renewable and abundant materials and have been seen as a good option as alternative materials for the production of particleboards. An example is the cardoon (*Cynara cardunculus* L.) fibers that possess good mechanical properties, suitable for structural applications where strength is important, and exhibit good thermal insulation properties [13]. Cardoon is grown mainly in the Mediterranean regions and has an average biomass yield of 7.5 ± 3.8 t ha^{-1}. It is a perennial plant with an annual growth cycle. At harvest, the plants are on average 2.1 m height and have a stalk diameter of 2.2 cm. The average weight of a cardoon plant in the field is 265.6 g, of which stalks represent about 59.1% of the total dry biomass [14]. In Portugal, cardoon is mainly grown for the value of the blue-violet pistils of the flowers that produce an extract rich in enzymes, namely cardosins, which are aspartic proteases capable of cleaving the k-casein present in fresh milk, thus curdling the milk for the production of some types of Portuguese cheese [15,16]. However, the cardoon biomass that results from cheese production is an agricultural by-product that, for the time being, has not been widely exploited and is undervalued, but which has the potential to generate a circular economy [17]. Thus, in this work, an environmental evaluation was made of the use of cardoon fibers as an alternative, renewable, biodegradable and inexpensive raw material for the sustainable production of particleboard panels.

On the other hand, traditional adhesives used in particleboard production are normally produced using non-renewable resources, and can have significant environmental and health hazards [12]. Thus, as part of the efforts currently being made to make particleboard production more sustainable, biodegradable materials of biological origin were developed for application as resins. More sustainable alternatives, such as soy-based or starch-based resins, are emerging as an ecological alternative to traditional resin adhesives, with lower VOC emissions or less toxicity to human health, and with better biodegradability. In fact, biopolymers (e.g., tannin, lignin, starch) are potentially more environmentally friendly, less dependent on fossil resources and guarantee good performance as adhesives [11]. In particular, starch is one of the most studied natural products as an adhesive due to its low cost, the fact that it is biodegradable, renewable and has good bonding properties, particularly for cellulose substrates. In 2018, the European Union produced 10.7 million tons of starch products, of which 58% were for human food, 2% for animal feed and 40% for non-food applications (mainly products for the paper industry) [18]. While starch-based resins offer environmental benefits, it is important to consider their limitations as well, in particular for applications where moisture resistance is essential [11]. Hence, it is important to assess their suitability based on the specific requirements of the intended application, and considering other factors such as performance, cost and availability of alternative materials.

The combination of cardoon particles with a starch-based adhesive is therefore a promising bio-based solution for low-density particleboards suitable, for example, for interior furnishings [13].

Although the use of renewable materials and the total elimination of non-renewable resources can contribute to a more sustainable and circular economy, as a matter of principle, such use must still be carefully evaluated from a life cycle point of view. Therefore, in order to assess their relative advantages over other options, identify possible environmental hotspots and guide decision-making toward reducing impacts, their production must be analyzed from a life cycle thinking perspective [19]. In this way, it is possible to assess their relative merits and identify the aspects that need to be improved for better performance and sustainability. Hence, this work aims to evaluate the environmental impacts of the life cycle of particleboards made from bio-based resources, in particular cardoon fibers obtained from *Cynara cardunculus* L. crop residues and a starch/chitosan-based adhesive, as described in the work by Monteiro et al. [13]. For the life cycle inventory, real production data obtained from a process carried out on a laboratory/pilot scale were used [13]. To the authors best knowledge, there are no previous LCA studies for the production of particleboards from cardoon, using starch/chitosan as adhesive.

2. Materials and Methods

2.1. Goal, Scope, Functional Unit, System Boundary

This study main goal is the evaluation of the life cycle environmental impacts of producing a particleboard using waste cardoon fibers and a starch/chitosan adhesive, based on the experimental/pilot scale results of Monteiro et al. [13], to identify the process hotspots, and propose improvements that will reduce the overall life cycle environmental impacts.

The methodology defined in the ISO 14040 [20] and ISO 14044 [21] standards was followed for the Portuguese/European context. The study is attributive, as the environmental impacts will be evaluated per functional unit.

The functional unit is a particleboard with dimensions of 220 × 220 × 16 mm^3. Hence, from a practical point of view, the LCA study can be used to obtain the Environmental Product Declaration (EPD) of the particleboard under study, following the EN standard 15084 [22] that defines its contents and how the environmental impacts of construction materials and parts should be reported. In the framework of the aforementioned standard, the functional unit corresponds to the declared unit that should be used when comparing similar products that may be used for similar purpose, whilst it is unclear what its final application will be, as several options are possible.

As for the system boundary (shown in Figure 1), the study follows a "cradle-to-gate" approach, considering the following life cycle stages: raw material production, adhesive preparation (component mixing and heating), cardoon fiber preparation (crushing and sieving), adhesive and cardoon fiber mixing, hot pressing and final processing.

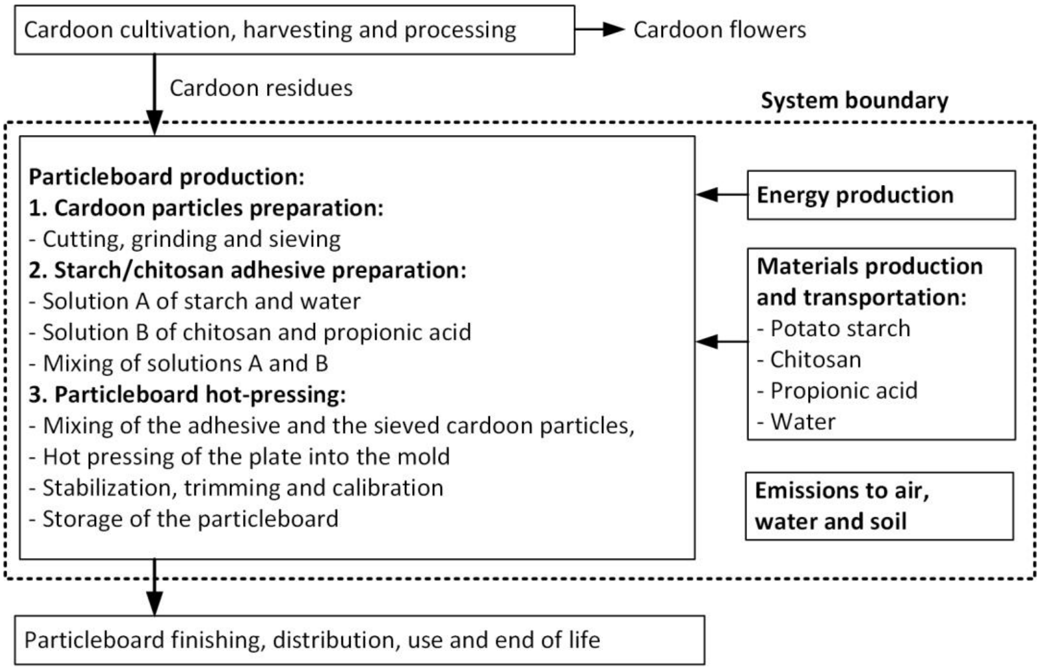


Figure 1. System boundary definition for the LCA study of particleboard production from cardoon fibers and with starch/chitosan as an adhesive.

Particleboard production can be broadly divided into three parts: (1) cardoon particles preparation, (2) adhesive preparation and (3) particleboard hot pressing. The main raw materials used for particleboard production are potato starch, water, chitosan, propionic acid and cardoon fibers. A fixed mass ratio of 0.8 was used between the adhesive and cardoon fibers [13]. To prepare the cardoon particles, the biomass is cut into smaller portions using a band saw (PINHEIRO/MAQTRAMA, Lda., Trofa, Portugal, SFM4-840) with 5500 W of power and is then ground in a blade mill (Retsch AS-300) with a power of 3000 W, obtaining smaller particles that are sieved (Retsch S-200) through a 430 W sieve to homogenize them. The biomass does not need any pre-drying treatment, as it has a low moisture content of 13%. All these unit operations take the same amount of time (5 min each).

To prepare the adhesive, potato starch and distilled water were mixed first. This mixing occurs almost instantaneously. Then, chitosan solution, at 5 wt% concentration, was prepared by mixing chitosan and propionic acid solution (6 wt%) for 3 h at 60 °C. This chitosan solution was added to the starch solution and mixed for 5 min. An automatic mixer with 1600 W of power was used for all these mixtures needed to obtain the bio-based adhesive for the panel. Then, to produce the particleboard panel the cardoon particles were blended with the adhesive system in a 2500 W laboratory paddle mixer (iMAL 00G3446) for 5 min. The final mixture is placed in a mold/tray (a square aluminum container, with 220 × 220 × 80 mm^3 dimensions), considering an adhesive/cardoon ratio of 0.8. The pressing was performed using a small computer-controlled scale/laboratorial press with 4000 W of power. Since it is necessary to preheat the press to 190 °C, in order to press the particleboard, two scenarios were considered with regard to the duration of the operation: (1) 65 min for summer conditions (summer scenario) and (2) 125 min for winter conditions (winter scenario). The hot plate pressing procedure itself involved pressing in two stages: (1) First, the cardoon/adhesive mixture in the mold was placed on the bottom plate and pressed to a 16 mm thickness for 60 s. (2) Then, the upper plate was raised to a 22 mm thickness and the particleboard was kept in the press for 240 s to allow the panel to expand. After pressing, stabilization follows, in which the particleboard remains at a temperature of 20 ± 2 °C and a relative humidity of 65 ± 5% until they reach a constant mass, as during the cooling period, they will lose some water. Finally, the panel is cut using a 1200 W squaring machine (MIDA SCE) for trimming the sides of the panel, which takes around 20 s, followed by the panel's thickness calibration using a 6000 W sander (Boere Select-1100 kk) for sanding the panel for 1 min. The final product obtained in this way is the particleboard, with 220 × 220 × 16 mm^3 dimensions, corresponding to this work's functional unit. The particleboard main characteristics were determined according to the applicable European Standards, in particular the density [23], moisture content [24], internal bond strength [25] and thickness swelling [26].

Although important for a more holistic understanding of the particleboard environmental impacts, the particleboard finishing, distribution, utilization and end-of-life stages were not considered in this study. Evaluating these final stages in the life cycle of particleboard poses a number of challenges due to the lack of information and data published in the literature. For example, there is no single final application for the particleboard, as it can be used for different purposes in both the construction and furniture industries. It would therefore be necessary to simulate its many applications, and even in these usage scenarios, the variability and uncertainty would be enormous due to lack of user data and information. Also, such an analysis is beyond the scope of this study, which focuses on the environmental analysis of the panel production process, produced from agricultural waste and with an adhesive system of renewable origin, following a "cradle-to-gate" approach.

2.2. Case Study Description: Particleboard Formulation

As described above, this work considers a specific case study, which aims to evaluate the life cycle of a particleboard produced from cardoon fibers with a potato starch/chitosan adhesive, based on the experimental work described by Monteiro et al. [13]. The adhesive consists of the following components: potato starch, distilled water, chitosan and propionic acid. The best initial formulation for the particleboard, according to Monteiro et al. [13] has the following components and characteristics:

- Starch/cardoon ratio (dry basis): 0.80;
- Chitosan/starch ratio: 0.05;
- Water/starch ratio: 1.75;

- Cardoon mass (wet basis): 0.113 kg;
- Initial moisture in the cardoon: 13%;
- Chitosan in the final solution: 5 wt%;
- Propionic acid solution: 6 wt%.

Based on these data, mass balances were carried out to calculate the quantities of each raw material entering the system under study, required for the life cycle inventory. The particleboards produced using this formulation had a final density, after stabilization, trimming and calibration, of 323 kg·m^{-3} with an internal bond strength of 0.35 N mm^{-2} and a thickness swelling of 15.2%.

2.3. Life Cycle Inventory Analysis: Data Source and Main Assumptions

The life cycle inventory (LCI) was carried out considering the production of particleboard with the formulation presented in the previous section. The inputs of materials (cardoon, chitosan, propionic acid, potato starch and distilled water) and the electricity needed for the process equipment, as well as the outputs (wastes, emissions) of the system under study, were accounted for in as much detail as possible.

Taking into account the study by Monteiro et al. [13], and the initial formulation and characteristics of the cardoon particleboard described above, it was possible to draw up the material balances required for the life cycle inventory (LCI) and calculate the quantities of each raw material needed to produce the panel. Since the cardoon used in this study was a waste product/by-product of cheese production, its cultivation, harvesting and processing were not considered in the inventory.

Regarding energy consumption, it was assumed that all the equipment uses electricity obtained from the Portuguese low-voltage energy mix, supplied through the Portuguese distribution grid, or from locally produced photovoltaic (PV) silicon panels. Hence, two scenarios for an electricity source were analyzed in this work. According to the production process described above, the energy consumption was obtained by knowing the equipment power, measured using an amperometric clamp (Fluke T6-1000) and the operating time (t). To determine the energy consumption associated with the adhesive heating, the Aspen Plus V9 program was used to simulate this unit operation.

The remaining LCI items, corresponding to background processes, were obtained from the Ecoinvent V3.5 database or from the literature. The latter was relevant in particular for chitosan, a compound that does not exist in the LCI database used in this work. To fulfil this gap, the information available in the work of Riofrio et al. [27], concerning the production of chitosan from shrimp processing waste in Ecuador was used. Additional modeling was required to obtain the inventory of glycerol, not directly available in the Ecoinvent database for all the glycerol lifecycle, from raw materials to the final product. Based on the data available in the LCI database, it was considered that glycerol was obtained as a by-product of biodiesel production, which is produced from rapeseed oil cultivated under European conditions.

Regarding the transportation of raw materials, a 50 km distance was assumed by the truck from the supplier to the production site, with the exception of chitosan for which the distance from the production site and ship transportation were considered [27]. For chitosan, sea transportation between the ports of Guayaquil/Ecuador to Leixões/Portugal via de Panama channel was assumed for an overall distanced of 5066 nautical miles/9382 km per ton of chitosan transported (https://sea-distances.org/), followed by a 50 km trip by truck.

2.4. Environmental Impact Assessment: Methods and Impact Categories

As the LCA study concerns particleboards widely used as building materials, either as construction elements or parts of furniture and other equipment, the standards ISO 21930 [28] and EN 15804 [29], in particular the latter, can be used to define which environmental impact categories should be used. However, as data from the literature of the environmental impacts of producing chitosan were used and no information was available in the EcoInvent V3.5 inventory database, a different approach was followed to ensure the internal study consistency. In particular, as the results of Riofrio et al. [27] were determined using the RECIPE methodology [30,31], this methodology was selected in this work. The calculations were performed in SimaPro V8.5 software for the 18 environmental impact categories considered in the RECIPE methodology. The environmental impacts due to the cultivation and processing of cardoon were assumed to be zero, as the cardoon biomass used corresponds to agriculture waste material in which the environmental impacts were attributed to the main product for which cardoon was cultivated (in this case was for cheese production).

2.5. Determination of the Volatile Organic Compounds Emitted by the Particleboard

Particleboard, in general, can contain VOCs and other pollutants that can be released into the environment (e.g., formaldehyde, phenol, toluene and benzene). These pollutants can affect indoor air quality, especially in poorly ventilated environments. To mitigate the risks associated with VOCs and other pollutants, control measures and regulations have been implemented in many countries. This includes setting limits on the emission of formaldehyde and other substances, as well as promoting the adoption of more sustainable production techniques and low-emission adhesives. In this work, the determination of specific VOC emissions in cardoon particleboard was carried out using the “active headspace” technique.

Specifically, a sample of material was cut into small pieces, with a total mass of 50.5902 g, which were placed in a glass impinger through which a stream of nitrogen passed. The VOCs were collected in Tenax TA tubes from this stream using a Casella Apex pump, being the flow measured by a primary flow calibrator Sensidyne Gilian Gilibrator 2.

A blank test, without any sample material, was performed before the test with the sample of particleboard.

These tubes were analyzed via gas chromatography, with identification and quantification using a mass selective detector (GC/MSD), Agilent Technologies model 7890A GC system and a mass selective detector of the same brand, model 5975C. The analysis was preceded by thermal desorption of the Tenax tube using a DANI model TD Master desorption system coupled to the GC. The analysis was performed according to ISO 16000-6 [32]. The VOC levels were calculated on the basis of the specific response factor for each compound, whenever possible. The levels of the other compounds were calculated based on the toluene response factor.

3. Results

3.1. Life Cycle Inventory

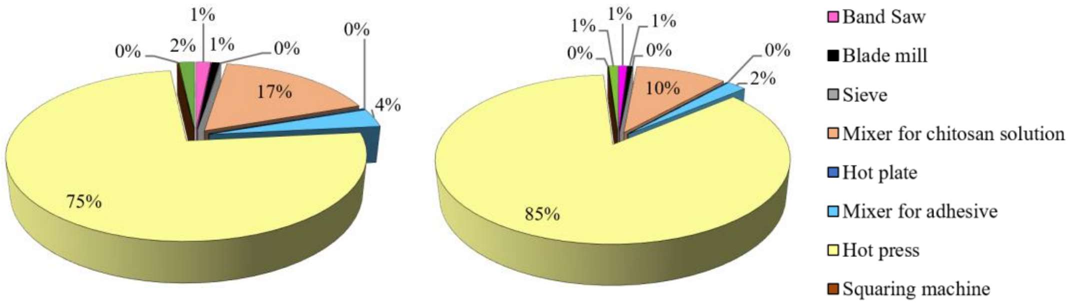
The life cycle inventory of materials and energy for the production of one particleboard with 220 × 220 × 16 mm^3 dimensions (functional unit), as described above, is shown in Table 1.

Table 1. Life cycle inventory for producing one particleboard (functional unit).

Raw Materials and Energy	Value
Dried cardoon, kg	9.83×10^{-2}
Potato starch, kg	7.86×10^{-2}
Chitosan, kg	3.93×10^{-3}
Propionic acid, kg	4.48×10^{-3}
Water, kg	2.08×10^{-1}
Electricity (summer scenario), kWh	5.79
Electricity (winter scenario), kWh	9.79

The analysis of the data presented in the table shows that the electricity consumption in the summer scenario is around 59% of that in the winter scenario, mainly due to the energy consumption of the press, which takes longer to heat up to the desired temperature in winter. The graph in Figure 2 shows the importance of each piece of equipment in terms of total energy consumption for the summer and winter scenarios.

It can be seen that the two main energy-consuming terms are the hot press (corresponding to 75% of energy consumption in the summer scenario and 85% in the winter scenario), mainly due to the need to preheat it to 190 °C, followed by the mixer for the chitosan and propionic acid solution (corresponding to 17% of energy consumption in the summer scenario and 10% in the winter scenario), due to its high viscosity [13] and duration (3 h) of the mixing operation at 60 °C. Then, the energy consumption in the mixer that is used to mix the starch and chitosan solutions and thus prepare the adhesive, corresponds to 4% of the energy consumption in the summer scenario and 2% in the winter scenario. The energy consumption of the other equipment units is very low compared to the already referred ones. In other words, the operations of cutting, grinding and sieving the cardoon, preparing the starch adhesive system, and the final stages of cutting and calibrating the cardoon panel, together account for less than 5% of the total energy consumption involved in the particleboard production. However, the process can be optimized to reduce the energy consumption associated with one particleboard production if the hot-press and other equipment units are used to produce more than one unit.



(**a**) (**b**)

Figure 2. Percentage of energy consumption for each piece of equipment in the (**a**) summer and (**b**) winter scenarios.

3.2. Environmental Impacts

Based on the RECIPE methodology [30,31] and the respective characterization factors for the impact categories, it was possible to determine the (overall) value of the potential environmental impacts. Table 2 shows the values of the environmental impact categories for one particleboard production, considering the summer and winter scenarios for the electricity consumption and for the electricity source, the Portuguese electric mix and its replacement by renewable energy generated locally using silicon photovoltaic panels.

Analysis of the results in Table 2 shows that the environmental impacts are significantly lower when the energy source is solar. As expected, the impacts of the summer scenario are also lower than those of the winter scenario. Regardless of the energy source and scenario considered, the following five categories stand out in descending order of impact value: marine ecotoxicity (MET), human non-carcinogenic toxicity (HET), human carcinogenic toxicity (HCT), terrestrial ecotoxicity (TET) and global warming (GW). These are therefore the main environmental impacts associated with cardoon particleboard production.

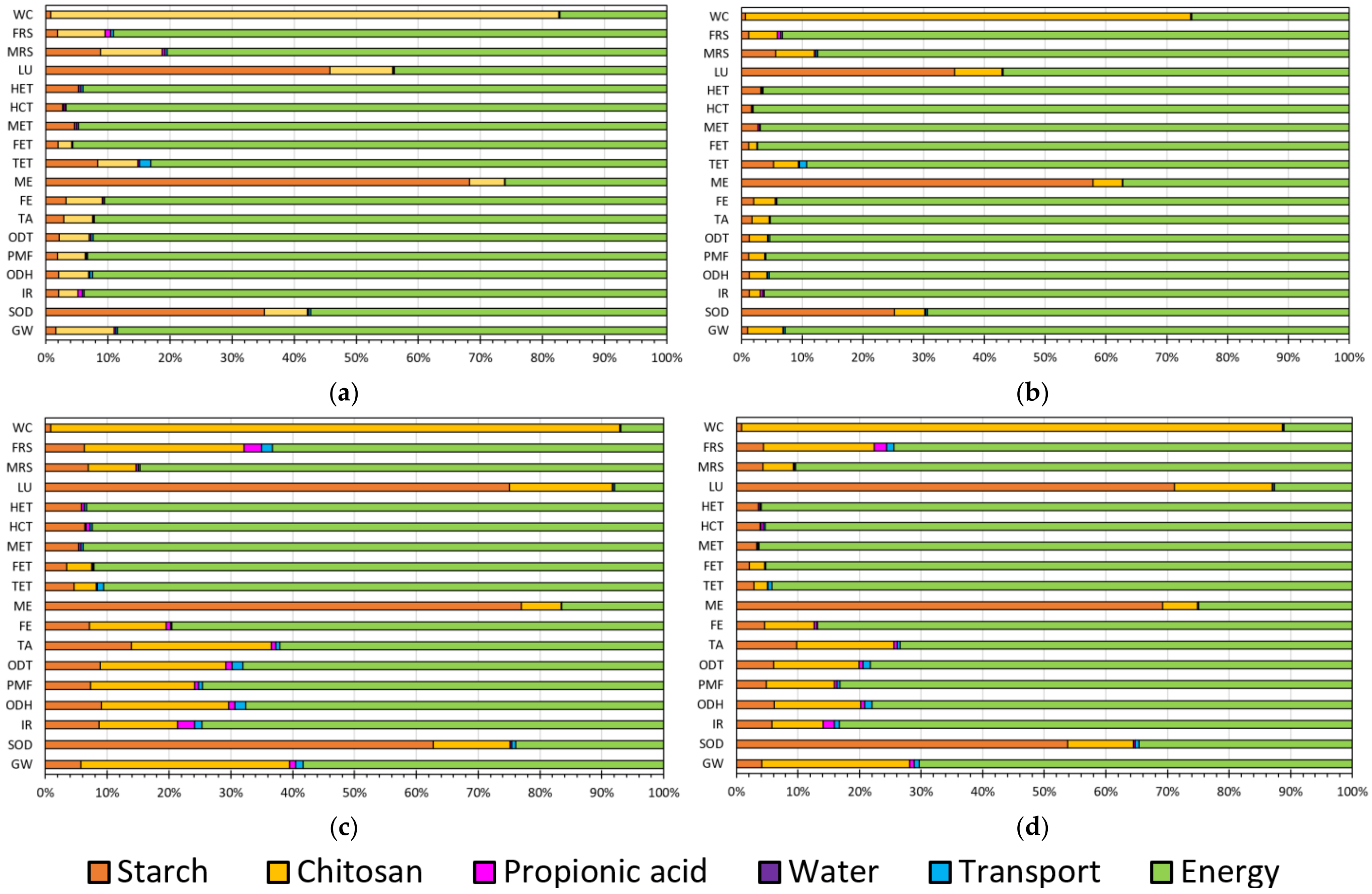
For most of the impact categories, the impact values are higher for the energy mix than for solar PV energy, with the exception of the mineral resource scarcity (MRS) and terrestrial ecotoxicity (TET) categories. The high difference between the two energy sources in the following impacts is noteworthy: fine particle formation (PMF), scarcity of fossil resources (FRS), global warming (GW) and ionization radiation (IR), which was to be expected given that the energy mix is mostly based on fossil resources.

Figure 3 shows the relative importance of each LCI item in each environmental impact category, considering the Portuguese energy mix and the photovoltaic (PV) energy for both the summer and winter scenarios. The figure shows that energy consumption is the dominant inventory item, with average contributions to the environmental impacts above 63% and values ranging between 7 and 97% within all four situations analyzed (energy mix, PV, summer and winter). That is mainly due to large energy consumption linked to the production of a particleboard, in particular the high temperatures required for the hot-press and mixing of the highly viscous chitosan solution. It can also be seen that the average contribution of energy to the impacts is lower when PV energy is used instead of the energy mix, mainly due to the burning of fossil fuels in the latter. Hence, one way of reducing the energy contribution to the overall environmental impact is to use renewable energy sources. In particular, the contribution of energy to the impacts is greater in the following categories: human carcinogenic toxicity (HCT), freshwater ecotoxicity (FET) and marine ecotoxicity (MET), with contributions of more than 90% within all four situations analyzed.

Table 2. Environmental impacts to produce one particleboard (functional unit) considering the different scenarios analyzed.

Impact Category	Acronym	Unit	Portuguese Energy Mix		Photovoltaic Energy	
			Summer	Winter	Summer	Winter
Global warming	GW	kg CO_2 eq	2.484×10^{-0}	4.001×10^{-0}	6.894×10^{-1}	9.670×10^{-1}
Stratospheric ozone depletion	SOD	kg CFC11 eq	2.272×10^{-6}	3.171×10^{-6}	1.274×10^{-6}	1.485×10^{-6}
Ionizing radiation	IR	kBq Co-60 eq	3.167×10^{-1}	5.218×10^{-1}	7.663×10^{-2}	1.161×10^{-1}
Ozone formation, human health	ODH	kg NOx eq	6.562×10^{-3}	1.075×10^{-2}	1.521×10^{-3}	2.231×10^{-3}
Fine particulate matter formation	PMF	kg $PM_{2.5}$ eq	5.411×10^{-3}	8.897×10^{-3}	1.418×10^{-3}	2.148×10^{-3}
Ozone formation, terrestrial ecosystems	ODT	kg NOx eq	6.600×10^{-3}	1.081×10^{-2}	1.576×10^{-3}	2.316×10^{-3}
Terrestrial acidification	TA	kg SO_2 eq	1.661×10^{-2}	2.718×10^{-2}	3.426×10^{-3}	4.894×10^{-3}
Freshwater eutrophication	FE	kg P eq	9.516×10^{-4}	1.546×10^{-3}	4.406×10^{-4}	6.826×10^{-4}
Marine eutrophication	ME	kg N eq	2.184×10^{-4}	2.576×10^{-4}	1.935×10^{-4}	2.155×10^{-4}
Terrestrial ecotoxicity	TET	kg 1,4-DCB	6.430×10^{-0}	1.012×10^{1}	1.153×10^{1}	1.874×10^{1}
Freshwater ecotoxicity	FET	kg 1,4-DCB	1.956×10^{-1}	3.247×10^{-1}	1.093×10^{-1}	1.788×10^{-1}
Marine ecotoxicity	MET	kg 1,4-DCB	6.461×10^{2}	1.069×10^{3}	5.516×10^{2}	9.090×10^{2}
Human carcinogenic toxicity	HCT	kg 1,4-DCB	6.667×10^{-0}	1.112×10^{1}	2.864×10^{-0}	4.690×10^{-0}
Human non-carcinogenic toxicity	HET	kg 1,4-DCB	4.939×10^{2}	8.146×10^{2}	4.426×10^{2}	7.278×10^{2}
Land use	LU	m^2 a crop eq	2.204×10^{-1}	2.871×10^{-1}	1.343×10^{-1}	1.416×10^{-1}
Mineral resource scarcity	MRS	kg Cu eq	4.310×10^{-3}	6.703×10^{-3}	5.510×10^{-3}	8.731×10^{-3}
Fossil resource scarcity	FRS	kg oil eq	5.791×10^{-1}	9.351×10^{-1}	1.725×10^{-1}	2.479×10^{-1}
Water consumption	WC	m^3	1.654×10^{-1}	1.850×10^{-1}	1.471×10^{-1}	1.541×10^{-1}

As shown in Figure 3, starch, followed by chitosan, is the inventory item with the second highest contribution to impacts, although when compared to energy, their relative importance is significantly lower, with average contributions of up to 18% within all four situations analyzed. The contribution of starch is more significant in the following impact categories: marine eutrophication (ME) with values ranging between 58 and 77% considering the four situations analyzed, followed by land use (LU), with values ranging between 35 and 75%, and stratospheric ozone depletion (SOD), with values ranging between 25 and 63%. Since starch is obtained from the cultivation and harvesting of potatoes, environmental impacts due to soil occupation and fertilizer consumption will occur. Therefore, the utilization of materials with lower environmental impacts may be relevant to reduce those impact categories. The contribution of chitosan is more significant in the following impact categories: water consumption (WC), with values ranging between 73 and 92%, considering the four situations analyzed. This is mainly due to the process of obtaining and processing chitosan, traditionally from the chitin in crustacean shells, and is therefore naturally associated with the use and consumption of water resources. The contribution to environmental impacts of other inventory items, namely propionic acid, water and transport, is significantly lower, being less than 1% for each inventory item within all four situations analyzed.



(**a**) (**b**) (**c**) (**d**)

Figure 3. Relative importance of each LCI item in the environmental impact categories considering the (**a**) summer and (**b**) winter scenarios for the Portuguese energy mix, and the (**c**) summer and (**d**) winter scenarios for the photovoltaic energy.

3.3. Volatile Organic Compounds in the Particleboard

Particleboards normally release different amounts of volatile organic compounds under different environmental conditions and depending on different factors. For example, their industrial production processes, in particular drying and hot pressing, potentiate the release of VOCs in highly variable quantities and chemical composition, also influenced by the interaction between the adhesive and cardoon fibers [33]. Biomass is composed of hemicelluloses, cellulose and lignin. Under certain conditions, such as in the presence of strong alkalis or water at high temperatures, hemicelluloses, which contain acetyl groups as side chains, can undergo hydrolysis. This hydrolysis of acetyl groups in hemicelluloses can lead to the formation of sodium acetate and the liberation of acetic acid [33].

In this work, by following the "active headspace" technique described in Section 2.5, it was possible to determine the concentration of VOCs present at the highest levels emitted by the cardoon particleboard. To note that formaldehyde was not evaluated in this study. Results are expressed in micrograms per cubic meter of nitrogen and the emission factor per mass of product per hour. The results are shown in Table 3.

Table 3. VOCs present in the particleboard obtained via GC/MSD analysis.

Compound	CAS	Concentration (μg/m^3)	Emission Factor (μg/(kg h))
2-Butenal	123-72-8	3.50	1.47
Acetic acid	64-19-7	398	167
2-Butanone	78-93-3	3.46	1.45
1-Methoxy-2-propanol	107-98-2	12.4	5.20
Propionic acid	79-09-4	12.4 *	5.22
Hexanal	66-25-1	2.77	1.16
Benzaldehyde	100-52-7	2.29	0.96
Benzyl alcohol	100-51-6	11	4.61
Undecane	1120-21-4	2.45	1.03

* Concentration calculated using the acetic acid response factor.

The results show that the cardoon particleboard contains a small variety of VOCs and, in general, the concentration of these compounds is low when compared to the acetic acid concentration, which has a value of 398 μg/m^3. This high release of acetic acid was also observed in composite materials with wood fibers, cork and other derivatives, justified by the degradation of hemicelluloses, present in lignocellulosic biomass, under thermal stress, which results in the removal of acetyl groups and consequent formation of acetic acid [34].

In the case of the cardoon particleboard, the formation of acetic acid is mainly due to the hot pressing process which, as it is carried out at a temperature of 190 °C, causes thermal stress that triggers the formation and emission of acetic acid. It can therefore be concluded that temperature and time are important factors contributing to the hydrolysis of acetyl groups. High temperatures increase the kinetic energy of molecules, making them more reactive, and promoting the hydrolysis of acetyl groups in hemicelluloses. The duration of exposure to high temperatures is also a significant factor as prolonged exposure can enhance the extent of hydrolysis. Hence, VOC emissions from particleboards generally depend on the type of adhesive used, with the use of starch adhesives being an advantage over formaldehyde adhesives, the parameters of the production process (pressing time and temperature) and storage conditions.

In addition, the release of VOCs from particleboard often occurs most prominently during the first few months after production, a release which is commonly referred to as "off-gassing". The release of VOCs is influenced by various factors (e.g., temperature, humidity, surface area of the particleboard exposed) and is most pronounced during the initial period when the adhesive is curing. Higher temperatures can accelerate the release of VOCs. Larger surface areas and increased ventilation can lead to a more rapid release of VOCs. As particleboard ages, the rate of VOC emissions tends to decrease over time. An adequate ventilation of indoor spaces can also help disperse the released VOCs [35]. These factors justify the fact that the VOC concentrations and emissions associated with cardoon particleboard are low, as 3 years pass between the production of the panel sample and its VOC analysis.

Thus, for a definitive assessment of the material, the determination of the VOC concentration should be repeated with a new sample of the cardoon particleboard in a test chamber. According to standards for this type of test (as EN 16516 [36]), testing shall begin within eight weeks of sampling provided that the sample remains in the specified packaging while stored at the laboratory. This procedure guarantees that the building materials tested are under the same conditions and can be comparable. The sampling and analysis of formaldehyde should also be included, in order to confirm that this cardoon particleboard using starch/chitosan as an adhesive has the advantage of emitting few VOCs when used inside buildings compared to panels of other materials and adhesives, and thus reducing the potential impact of its use in human health.

It is important to note that not all particleboards and adhesives are equally produced, and emissions can vary based on the specific materials and manufacturing processes used. Manufacturers may use low-emission adhesives or implement measures to reduce VOC release [35]. For example, to minimize potential exposure to VOCs, it is advisable to allow newly produced particleboard to "off-gas" in a well-ventilated area for a period of time before using it in enclosed spaces, especially in applications like indoor furniture where human exposure is a concern [37]. Additionally, choosing products labeled as low-emission or meeting specific emission standards can help mitigate potential health impacts.

4. Discussion

The results presented in the previous section show that the controlling factors for the particleboard environmental performance are the consumption of energy, starch and chitosan. Thus, a focus should be given to reduce their consumption or replace them by options with lower environmental impacts.

Although it would be interesting to compare, from an LCA point of view, the use of starch and chitosan with the classic petroleum-based polymers traditionally used in the production of particleboards, it was not possible to do so in this study due to lack of adequate data. To be able to make this comparison correctly, it would be necessary to obtain data on an experimental/pilot scale with the same type of equipment units that were used in this work for particleboards using petroleum-based polymers.

Concerning the materials, their substitution requires practical feasibility analysis, as particleboards have to follow strict quality criteria to be commercialized and used in practice. As no information could be found for alternative materials, only the influence of energy was analyzed in this work, by comparing the electricity obtained from the Portuguese low-voltage energy mix, supplied through the Portuguese distribution grid, or from locally produced PV silicon panels.

With the use of photovoltaic energy, there has been a reduction in the contribution of energy to environmental impacts, namely in the categories of LU, SOD, WC, ME, GW, ODT and FRS, among others. For the impact categories where energy is not the dominant factor, the reductions were negligible and in other cases, such as for mineral resources (MRS) and terrestrial ecotoxicity (TET) categories, there was even an increase, as expected. This is due to the production of solar panels, in particular of the silicon used in the panels [38]. Moreover, the utilization of metals such as chromium and copper in the electrical cables and support equipment, results in a higher environmental impact in the category MRS, as they correspond to the non-renewable resources [39].

Although the use of renewable energies contributes to reducing environmental impacts in this study, energy consumption remains the most important environmental impact for the product considered. More energy-efficient equipment can therefore be used, particularly for hot pressing, mills and/or sieves. This study showed that the hot press equipment is responsible for the highest energy consumption (>75%). Regarding the hot press, integrating technologies to optimize energy consumption during pressing can lead to energy savings and a reduction in operating costs. Also, implementing advanced automation and control systems can improve operational efficiency, reduce cycle times and increase production output. In addition, upgrading to more precise control mechanisms can ensure consistent pressing, resulting in higher-quality end products. With regard to mills, improving the design and efficiency of mills can increase the milling rates, reduce processing time and thus, energy consumption, and improve the overall production capacity. In addition, the introduction of sensors and predictive maintenance technologies can reduce downtime, increasing equipment reliability. In addition, the implementation of advanced particle size control systems can ensure more consistent production and meet specific product requirements. With regard to sieves, incorporating more advanced sorting technologies can improve the accuracy of particle separation, leading to higher-quality end products. In addition, designing sieves with more efficient screen-changing systems can reduce downtime during maintenance. Furthermore, implementing dust suppression systems can improve working conditions and comply with environmental regulations. Therefore, investing in equipment upgrades is a strategic approach to increase efficiency and energy savings, help reduce operating costs, maintain competitiveness, comply with evolving industry standards and improve the overall operational performance. Equipment improvements often result in higher production rates, leading to increased overall productivity. Better control over processes can result in higher-quality final products. Predictive maintenance and improved design can increase equipment reliability, reducing downtime. Upgrades to meet environmental and safety regulations can contribute to sustainable and compliant operations. However, a more in-depth analysis of the technical aspects related to the process equipment is beyond the scope of this study.

Another option to reduce energy consumption involves a more optimized use of the press, namely, to press more than one particleboard per production cycle. Despite the energy-saving potential of this measure, there are also implications for the energy consumption of the other equipment units, since more material will have to be processed upstream of the press in order for it to be able to press more particleboards per cycle. Therefore, the option analyzed in this work, which involves replacing the electricity source with a renewable one, is easier to implement without risking the particleboard quality. In particular, the Portuguese electric mix was replaced by renewable energy generated locally using silicon photovoltaic panels. In addition to the potential reduction in environmental impacts, local PV electricity production allows companies to reduce their energy costs and contributes to the decarbonization of their activities, currently a strategic objective in the European Union. The results show that in the GW/carbon footprint category, there are significant reductions of around 34% and 24%, respectively, in the summer and winter scenarios, by replacing the Portuguese energy mix by photovoltaics energy.

Despite the environmental advantages of using solar energy to offset the amount of energy from the grid, particularly for the goal of decarbonizing industry, its intermittency limits its ability to fulfill demands consistently. In theory, it is possible to supply all the needs of a manufacturing industry with photovoltaic panels, especially if there is investment in more efficient technologies and energy storage to deal with the periods without sun. However, its feasibility depends on several factors [40], such as the industry's energy consumption, the efficiency of the photovoltaic panels, the geographical location and climatic conditions of the region, the existence of energy storage solutions (such as batteries) and energy efficiency practices. Although PV electricity may not be the only solution, a combination of these factors and technologies could lead to a significant reduction in dependence on traditional energy sources in manufacturing industries.

Other renewable energy sources could also be explored or used alongside PV electricity to supplement the energy needs of the process and also for the transport of raw materials and distribution of finished products. Examples include the wind energy to supply electricity to the process equipment and/or liquid biofuels (biodiesel and bioethanol), for example, produced from marine microalgae or biowaste [41], to replace fossil fuels in vehicles for raw material transportation and distribution of the final product.

Concerning wind energy, it is inherently intermittent and variable, since wind turbines only produce electricity when the wind blows within a certain speed range. This variability can lead to challenges in maintaining consistent energy production, and requires effective energy storage solutions. Not all locations are suitable for the efficient production of wind energy. Usually, ideal locations are in coastal regions, mountain tops, or open plains, requiring significant land area, which may compete with other land uses, such as agriculture or conservation. Developing the infrastructure needed to transmit electricity from remote wind farms to the point of use can be challenging and costly. In addition, wind turbines produce noise, which has an impact on local communities and wildlife, particularly birds and bats.

On the other hand, while biofuels from biowastes or microalgae offer a promising avenue for sustainable energy production, there are still some limitations and challenges associated with their production and implementation. For example, the composition and quality of waste materials can vary widely, depending on the source and type of waste. This variability can pose challenges in standardizing biofuel production processes. Waste streams may contain contaminants or impurities, such as heavy metals or pollutants, which can interfere with the biofuel production process. Waste collection infrastructure, logistics, and availability are crucial factors. Certain types of waste, such as agricultural residues, may be available seasonally. This can create challenges for maintaining a consistent feedstock supply throughout the year. Some waste materials may require extensive pre-treatment to make them suitable for biofuel production. Pre-treatment processes can add complexity and cost to the overall production chain. The technologies for converting various waste materials into biofuels are still evolving. Investment in research and development is necessary to optimize processes and make them more cost-effective. Advances in waste-to-biofuel conversion technologies, coupled with effective waste collection and preprocessing strategies, will play a crucial role in realizing the full potential of biofuels from wastes.

5. Conclusions

The environmental impacts of producing particleboards using renewable materials, in particular starch and waste materials from cardoon processing, were determined via a "cradle-to-gate" LCA study. A case study based on experimental/pilot scale data was used to obtain primary data that were complemented with information from the LCI database EcoInvent V.3.5 and the literature. The calculations were performed with the Simapro software V 8.5.2 using the RECIPE methodology. The results show that energy consumption is the dominant inventory item and the main contributor to most environmental impact categories. The utilization of renewable energy and more efficient equipment, or more suited to the materials to be processed, would be an interesting option to improve the process of environmental performance. The effects of replacing the electricity source from the Portuguese low-voltage electricity mix to locally produced Photovoltaic electricity using silicon panels were evaluated. Significant reductions were observed in most of the environmental impact categories, for example, a 34% reduction in the carbon footprint. Further developments in the production process or even the replacement of raw materials used in the adhesive system could improve the environmental performance of the process from a life cycle perspective.

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