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Sustainable Environmental Analysis of Wooden Boxes for Fruit and Vegetable Packaging and Transport in Comparison with Corrugated Cardboard Boxes

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Abstract: This study analyses the environmental sustainability of using wooden boxes (WBs) compared to corrugated cardboard boxes (CCBs) for the transport of fruit and vegetable products, where the same box size between WB and CCB is assessed and compared. The Life Cycle Assessment (LCA) followed ISO 14040:2006 and ISO 14044:2006 standards, using the ReCiPe 2016 MidPoint methodology. The following impact categories analysed for sustainability impact, evaluation and monitoring are included: global warming potential, acidification, eutrophication, human toxicity and abiotic resource depletion. The study covered all the stages of packaging life through cradle-to-grave analysis. The study results show that CCBs have a higher environmental impact across most categories despite being single-use packaging systems. The comparison between both packaging systems shows that WBs are a more sustainable alternative, with lower overall environmental impacts in fruit and vegetable packaging and transport. As a general conclusion, WBs have a lower overall environmental impact than CCBs, especially in the key impact criteria of global warming potential, acidification, eutrophication, human non-carcinogenic toxicity, fossil resource depletion and water consumption. Due to that, the wooden box is a more sustainable material for fruit and vegetable packaging, logistics and transport than the corrugated cardboard box, considering the scope and destination analysed.

Keywords: sustainable materials; Life Cycle Analysis; fruit and vegetable packaging; cardboard boxes; wooden boxes; monitoring sustainability

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1. Introduction

The agricultural sector is one of the fundamental pillars of the European Union's economy. Spain exports the most fruit and vegetable products in the EU, with approximately 11.3 million tonnes exported in 2023 [1]. The agri-food value chain contributes almost 9% of national GDP, 11.3% of employment, and accounts for 18.5% of the country's exports of goods [2]. Germany is the sector's leading export destination. This market volume reinforces the importance of the sector and the proper use and study of packaging in the export of products.

In the EU, Directive 1935/2004 [3] defines the regulatory framework for the properties and requirements of food contact packaging. LCAs have established themselves as a standard methodology for assessing the environmental impact of products throughout their life cycle stages [4].

The primary packaging for transporting food products is corrugated cardboard and wood as single-use packaging and plastic packaging as reusable packaging [5]. However, the demand for more environmentally friendly alternatives for packaging is becoming more and more critical, so studies based on the life cycle of the product are becoming more and more critical; although we know that wood and cardboard are of biological origin and are therefore presumed to be more environmentally friendly, perhaps the casuistry of the life cycle of the packaging of a particular product may suggest a better option for using one material or the other.

Therefore, in recent years, many studies have been carried out linking agricultural packaging to environmental performance, such as ECOBILAN 2000 [6]; Sauer et al. (2004) [7]; Singh et al. (2006) [8]; Albrecht et al. (2009) [9]; Levi et al. (2011) [10]; Albrecht et al. (2013) [5]; Franklin Associates (2016) [11]; Bala and Fullana (2017) [12]; Pauer et al. (2019) [13]; Fullana (2020) [14]; Lo-Iacono et al. (2020–2021) [15,16].

Today, only four studies have analysed wooden packaging [5,6,9,17,18]. The rest mainly compared single-use corrugated cardboard vs. reusable plastic crates. The last study on wooden packaging was carried out in 2013 [5]. Differences can be observed among the studies. For example, the ADEME study [6] showed that reusable packaging has lower environmental impacts than single-use cartons, as shown in another analysis [14]. However, in 2005 [19], it was shown that single-use packaging has a lower environmental impact than reusable packaging, as it is also supported by Lo-Iacono [15]. The main difference in results among those studies was the geographic scope, as these last studies analysed international markets, while reusable packaging was more beneficial in national market analysis.

In recent years, wooden packaging has been optimised by including new material, medium-density fibreboard (MDF), optimisation of adhesives and thicknesses, machinery and technology in general.

For these reasons, a deep review of the life cycle of wooden packaging is considered necessary to compare it with other fruit and vegetable packaging, specifically with corrugated cardboard packaging [15].

2. Materials and Methods

The LCAs have been carried out following ISO 14044:2006 and 14040:2006 [20,21] standards, which specify the principles, requirements and guidelines for quantifying the leading environmental aspects and potential impacts of an industrial product. According to these standards, an LCA must include the phases specified in Figure 1.

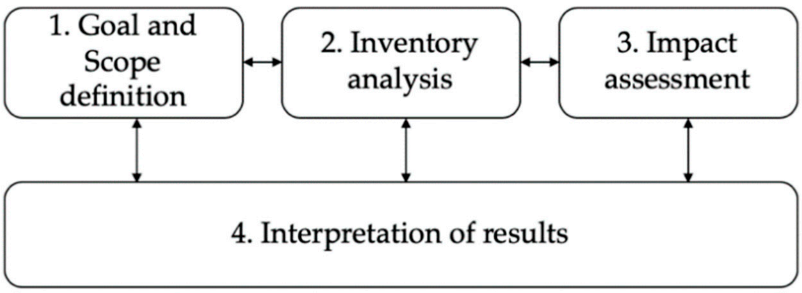

Figure 1. LCA method applied following ISO 14040 and 14044.

Inventory analysis refers to the collection of data and calculation procedures to quantify the inputs and outputs to the product system throughout its life cycle. The following steps are data collection, validation of collected data and relating the data to the unit processes and the functional unit.

The impact assessment phase aims to assess the significance of potential environmental impacts through the data collected in the previous inventory. In this process, the data collected are associated with specific environmental impact categories according to the chosen analysis methodology. This phase serves as a basis for the interpretation of the results.

The interpretation of results considers the results of the inventory analysis and the impact assessment together. This phase should include the identification of significant emissions from the quantification results of the inventory analysis and life cycle impact assessment phases, evaluating the analyses with completeness, sensitivity and consistency, and the conclusions, limitations and recommendations. Furthermore, the interpretation should include a quantitative/qualitative assessment of uncertainty. In addition, the allocation methods selected in the report should be detailed, and the study's limitations should be identified. Finally, this study has been reviewed by a panel of three international experts, fulfilling the requirements established by the standard ISO 14044:2006 (see Appendix A).

2.1. Goal and Scope

The main objective of the LCA of wooden boxes (WBs) is to determine the environmental impact of their use in the export of fruit and vegetable products and to compare them with their main competitors in the market, specifically focusing on the comparison with corrugated cardboard boxes (CCBs).

(a) Product selection

The product selection has been made based on interviews with 20 representative wooden packaging manufacturers in Spain. The selected, most widely produced and representative WB in the sector is called the Pitufo®. The ISO-UNE 49051 [22] standard indicates its characteristics. The capacity of a Pitufo® WB is supported by a load of 1 kg to 3.5 kg. The dimensions are a maximum of 300 × 200 mm (Figure 2).

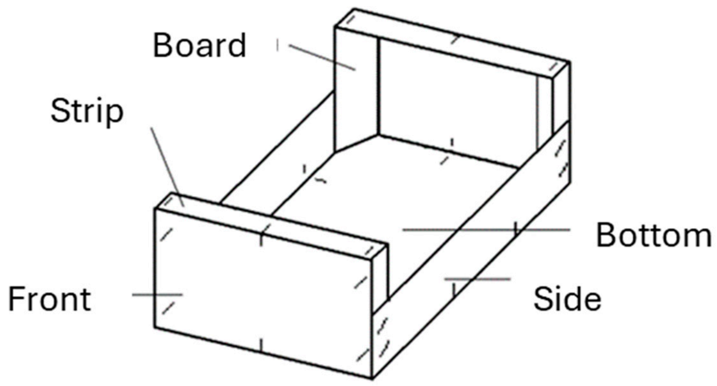

Figure 2. Pitufo® wooden packaging (300 × 200 mm) corresponding to ISO-UNE 49051.

The WB is made of different materials: slats of solid wood for the boards, medium-density fibreboard (MDF) for the bottoms and plywood for the fronts and sides. The solid wood pieces are usually manufactured with pinewood, using the different species of industrially relevant species available in Spain, mainly *Pinus pinaster*, *P. halepensis*, *P. radiata*, *P. nigra* and *P. sylvestris*. The plywood board is usually made from different poplar clones (*Populus x euroamericana*), generally three layers of rotary veneer. MDF is made from long-fibred woody species, mainly pine, eucalyptus and poplar, to a lesser extent.

A meeting was held to determine the international target markets for exporting fruit and vegetable products with a group of Spain's most representative fruit and vegetable exporters. Analysing the data provided by the companies, we can select mandarins as the most exported fruits with the Pitufo® WB, as is shown in Figure 3.

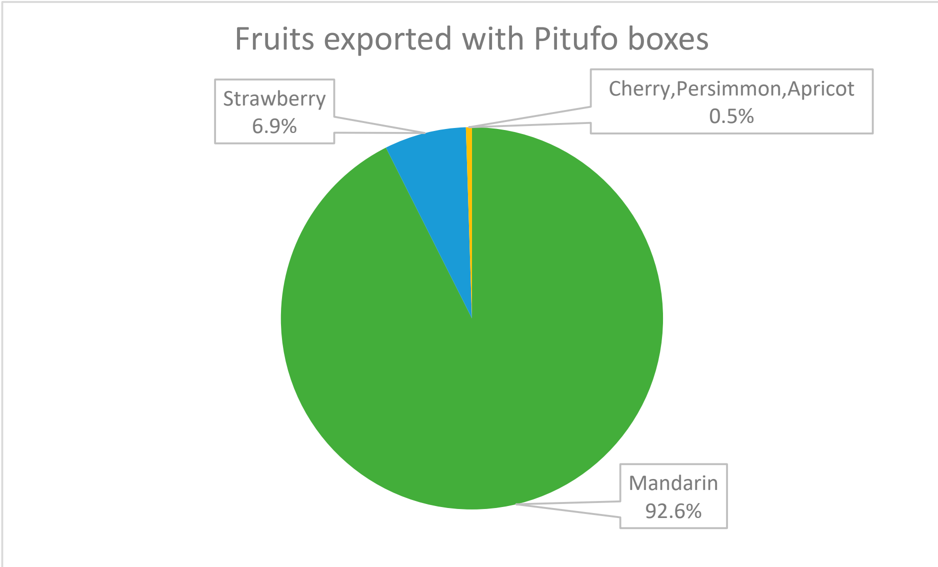

Figure 3. Most exported fruits in the Pitufo®'s boxes (in %).

Also, following the data provided by the companies, according to importing countries, we find that 70% of exports are destined for France and Germany (Figure 4). So, the main products exported in Pitufo® are mandarins, and the main destination market for this type of packaging is Germany, with around 35% of the total exports from Spain.

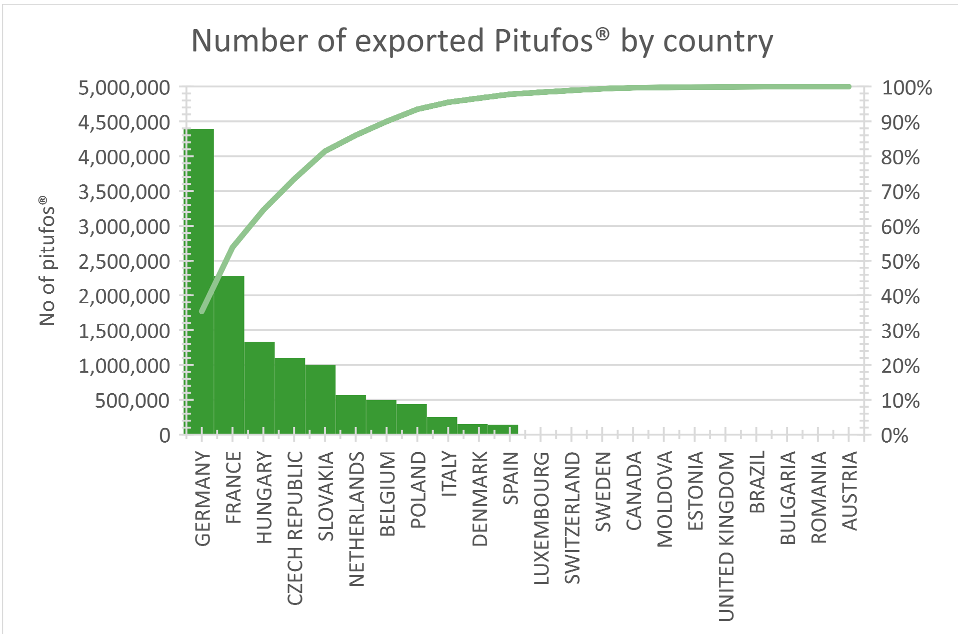

Figure 4. Number of exported Pitufos® by country.

(b) Functional Unit (FU)

The FU considered and defined for the LCA is established as: a 'packaging system to adequately store and transport 1000 tonnes (t) of mandarins from the market of origin, located in Valencia, to the market of destination, located in the centre of Germany, specifically in Hannover, with a distance of 2000 km.'

The quantity of containers necessary to transport 1000 tons of mandarins to the destination market is calculated. Transport to the destination market is carried out in refrigerated trucks with a 40 t load capacity. However, according to the information gathered from the companies consulted, given the low density of the products transported and the conditions they must be stored in, each truck carries 26 pallets loaded with the containers and the product. Generally, packaged fruit and vegetable products are transported on 1200 × 1000 mm pallets, and an average of 420 Pitufo® fit on both WBs and CCBs in the total truckload (see Table 1).

Table 1. Real load of the boxes to define how many are included in the functional unit.

	Theoretical Load (kg)	Actual Load (kg)	Number of Boxes
Pitufo® WB	2	2.3	434,783
CCB	2	2.3	434,783

After the FU calculation, the transport phase is defined. Each truck transports an average product load of 25,116 kg of mandarins. To this, the weight of the 26 pallets must be added, approximately 500 kg (at almost 20 kg per pallet). In the case of Pitufo®, an additional weight of 3 tonnes of WBs has to be added, while in the case of CCBs, 1 tonne has to be added (see Table 2).

Table 2. Distribution data of packaged products.

	Dimensions (mm)	Box Weight (g)	Number of Boxes per Pallet	Pallets/Truck 24 t	Num of Boxes per Truck	Total Weight of Boxes
Pitufo® WB	280 × 190 × 110	280	420	26	10,920	3057 kg
CCB	300 × 200 × 100	100	420	26	10,920	1092 kg

Therefore, the total loads of the two packaging systems for the transport of the FU are:

- Trucks with Pitufo® WBs: 28,674 kg;
- Trucks with CCBs: 26,616 kg.

2.2. System Limits

The cradle-to-grave system boundary is established following ISO 14044 (Figure 5). A cradle-to-grave LCA has been chosen because, in the export of fruit and vegetable products, both WB and CCB packaging cannot be reused for the same purpose. Therefore, once the packaging reaches its destination, the end of useful life is applied according to the country where this end of life occurs, in our study's case, Germany.

Figure 5. Graphic definition of life cycle stages.

Furthermore, the LCA's geographical and temporal limits are also defined by ISO 14044:2006 [20].

- **Geographical limits:** The fruit- and vegetable-packaging manufacturing system is limited to Spain. Pine, poplar and eucalyptus wood are almost entirely supplied domestically to the different elements of the WB. In the case of CCBs, the supply of raw material (cellulosic pulp), paper and corrugated board is also usually domestically produced. However, it can also be imported from other EU countries.
- **Time limits:** The base year of the study is 2022. In addition, it should be noted that some process data from 2015 to 2023 has been considered.

The system boundaries determine which unit processes are to be included within the LCA, following ISO 14044:2006 (Section 4). Thus, the LCA design has ensured that the selection of system boundaries and the exclusion of steps are consistent with the study's objectives.

(a) System boundaries for WBs

The system boundaries considered for WBs are defined based on the product life cycle specified in ISO 14044:2006. Thus, the stages of the life cycle of the Pitufo® WB are as follows:

- **Raw material extraction:** includes processes related to the extraction of raw materials and their preparation, i.e., the extraction of the tree in the forest, energy consumption in forestry operations, and transport of raw material to the primary wood processing industries (sawmills, plywood and MDF factories).
- **Manufacture of WB base materials:** this stage includes the processes in the sawmill (sawing of logs, sawing and drying of slats), plywood mill (production of rotary veneers, drying and ironing of veneers, forming, gluing, pressing and curing of three-layer boards) and MDF mills (chipping, shredding, drying, gluing, blanketing, felting, cold pre-pressing, hot pressing and curing of boards), as well as transport to the WB manufacturing plant.
- **Manufacturing of WBs:** processes that transform panels and solid wood into ready-to-market Pitufo® WBs: mitring of strips, cutting and guillotining of strips and sides and ends of plywood panels, cutting of MDF bottoms (and sides and ends), assembly, stapling and marking.
- **Distribution:** Transport of pre-packed fruit and vegetable products to the destination market. Refrigerated trucks carry out this distribution with a maximum load capacity of 40 tonnes.
- **End of Life:** This is the entry into the waste management system, where the WB can be recovered as a whole material in recycling for the manufacture of particleboard or recovered as an energy source in combustion, cogeneration or gasification processes. The third option is biodegradation and composting in landfills.

(b) System boundaries for CCBs

Based on this reference bibliography [4–7,15,16,18], the corrugated board packaging (CCB) lifecycle scope has been set. The scope at the different stages of the LCA is as follows:

- **Raw material extraction:** includes processes related to the extraction of raw materials and their preparation, such as forest harvesting, energy consumption of harvesting and transport of the raw material to the pulp and paper mills.
- **Manufacture of CCB materials:** manufacturing processes of the different types of paper from forest-based raw materials or recycling (Kraft, semi-chemical, etc.) and paper and corrugated board manufacturing processes (boards with *flutings* and *liners*).
- **CCB manufacture:** cutting and manufacturing processes of the CCB, in our case, 30 × 20 cm.
- **Logistics:** transport over the distance to the export market in refrigerated trucks with a maximum load capacity of 40 t.
- **End of Life:** the entry into the waste management system and the type of end-of-life treatment applied to the CCB.

For the CCBs, the life cycle for the refrigerated transport of mandarins from Spain to Germany is shown in Figure 6.

Wherever possible, data from recognised government agencies and institutions, manufacturers' data sheets and direct interviews with producers have been used. Where this type of field information was unavailable, the ECOINVENT 3.9 databases and literature sources have been used.

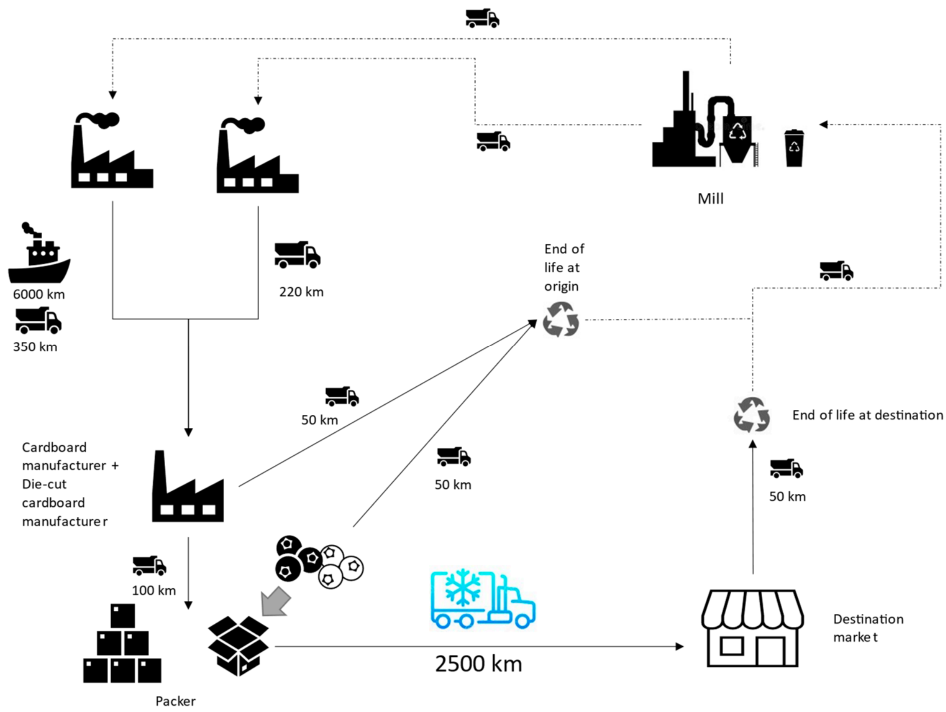

Figure 6. The life cycle of CCB packaging used for refrigerated transport of mandarins from Spain to the German market.

(c) Exclusions

This study does not consider the environmental impacts associated with the maintenance of the industrial manufacturing or logistics machinery used in the different phases of the processes or the transport of employees to their workplaces. Additionally, as stated in ISO 14044:2006, cut-off criteria can be applied based on the amount of material, energy or environmental significance associated with the unit processes or product system to exclude them from the LCA. In addition, due to the comparative nature of this study, the input standards for both systems have been excluded. These exclusions mainly affect flexographic inks, low-density polyethylene film, the product packaging process and the transport of the mandarins from the crops to the packaging warehouse. However, it is essential to highlight that this study does take into account both the energy consumption of the machinery in all industrial and logistical processes and the total water consumed in these processes, as well as the transport of raw materials to the production mills.

2.3. Methodology Employed for the Results Analysis and Impact Categories Analysed

The data analysis methodology used is ReCiPe 2016 [23] at MidPoint. It includes the following impact categories:

1. **Global Warming Potential:** the global warming potential of GHG emitted during the product life cycle, measured in CO_2 eq.
2. **Acidification**: contribution to the acidification of soil and water due to the emission of acidic substances, measured in SO_2 eq.
3. **Eutrophication:** release of nutrients into the environment, which can lead to excessive growth of algae and plants, negatively affecting aquatic ecosystems, measured in PO_4 eq.
4. **Human toxicity:** potential toxic effects on human health due to exposure to harmful chemicals, measured in “human toxicity units”.
5. **Abiotic resource depletion:** use and depletion of non-renewable natural resources, such as minerals and fossil fuels, and water consumption, measured in “units of mass of an abiotic resource depleted”.

2.4. Inventory Analysis

Inventory analysis involves data collection and calculation procedures to quantify the relevant inputs and outputs of the product system for the entire life cycle. This section describes the detailed inventory analysis for each material type of CCBs and WBs.

2.4.1. Inventory Analysis of WBs

The LCA of WBs starts from the extraction of the raw material, followed by the first transformation of woodworking industries that are in charge of transforming roundwood into products that will later be used in the production of wooden packaging. The products derived from the first transformation are MDF (fibreboard manufacturing industries), plywood (rotary veneer and plywood mills) and slats (sawmills). Figure 7 graphically defines the life cycle of WBs. Blue squares mean that the data have been obtained from official databases, and green squares mean that the data have been obtained directly from the mills.

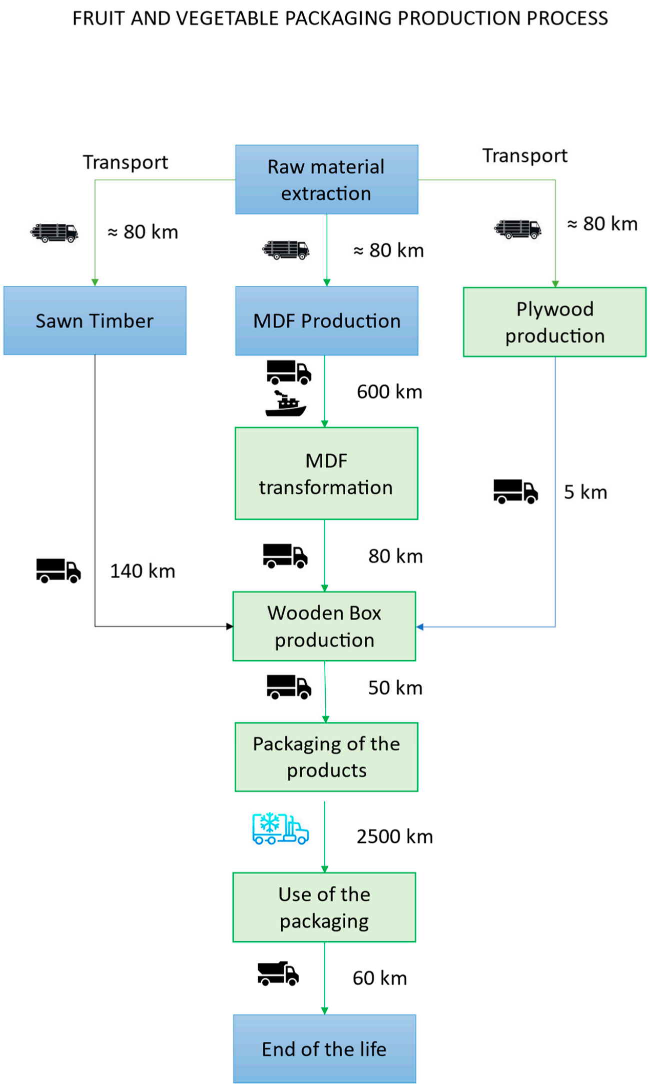

Figure 7. Life cycle processes of WBs and average transport distances.

MDF data, including timber harvesting, transport, and industrial board manufacturing, have been obtained from the ECOINVENT database. An inventory analysis of the process of board adaptation for the WB manufacture has been carried out. For this purpose, the unitary processes of board adaptation have been defined. The unit processes are shown in

Figure 8. In material adaptation, the MDFs are surface-finished by painting and curing up to four times per board. Subsequently, the MDFs are cut to the desired dimensions for use as bottoms in the WB (see Figure 2).

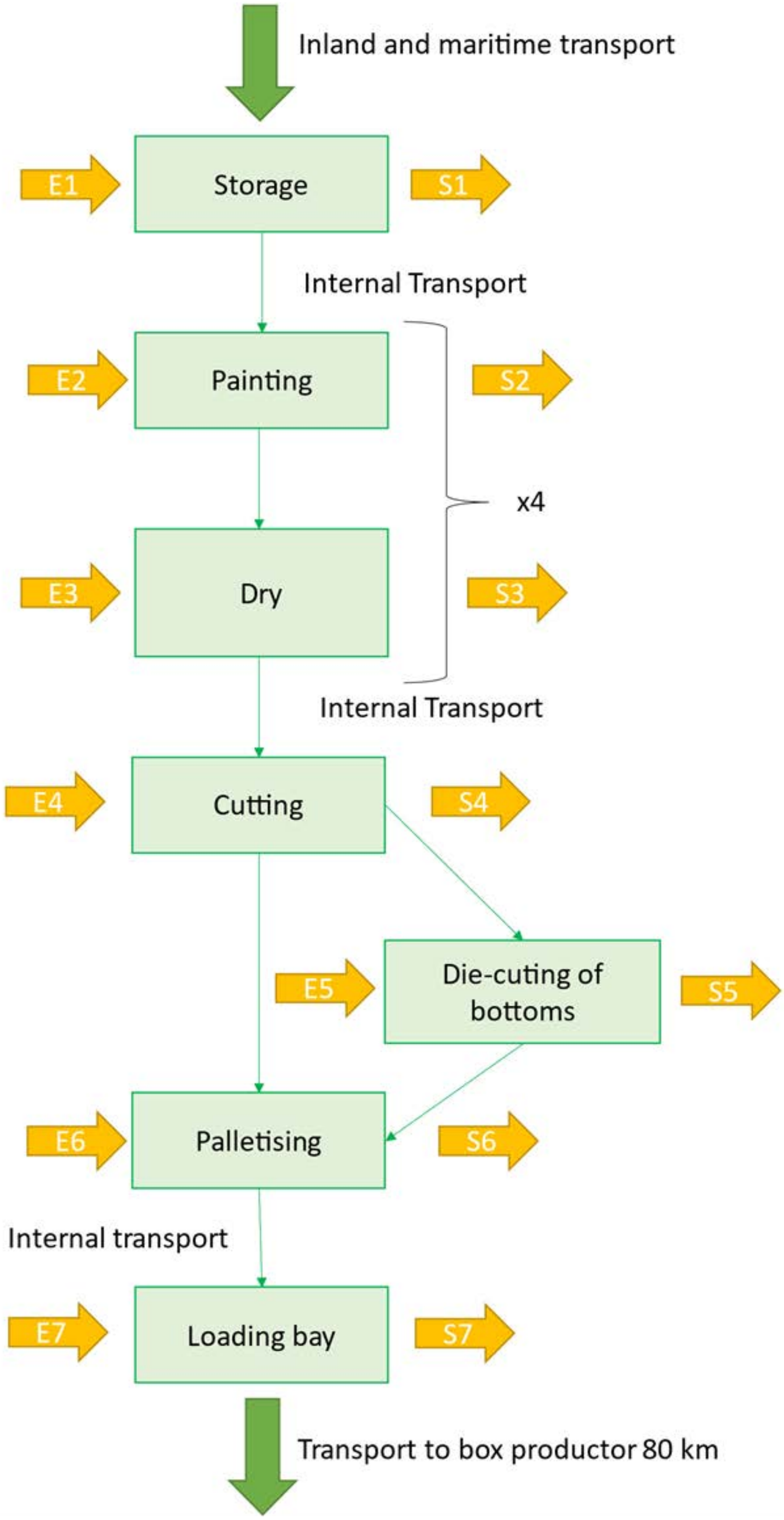

Figure 8. Unit processes for the adaptation of MDF boards.

Three bonded rotary veneers of approximately 1 mm thickness each generally compose the plywood, with a core layer and outer layers (face and back) glued with alternating wood grain orientation. The plywood inventory analysis was carried out on-site in the primary industries that supply it to the WB manufacturers in Spain. Figure 9 shows the flow chart of plywood production for the final use as fronts and sides of the WB (see Figure 2).

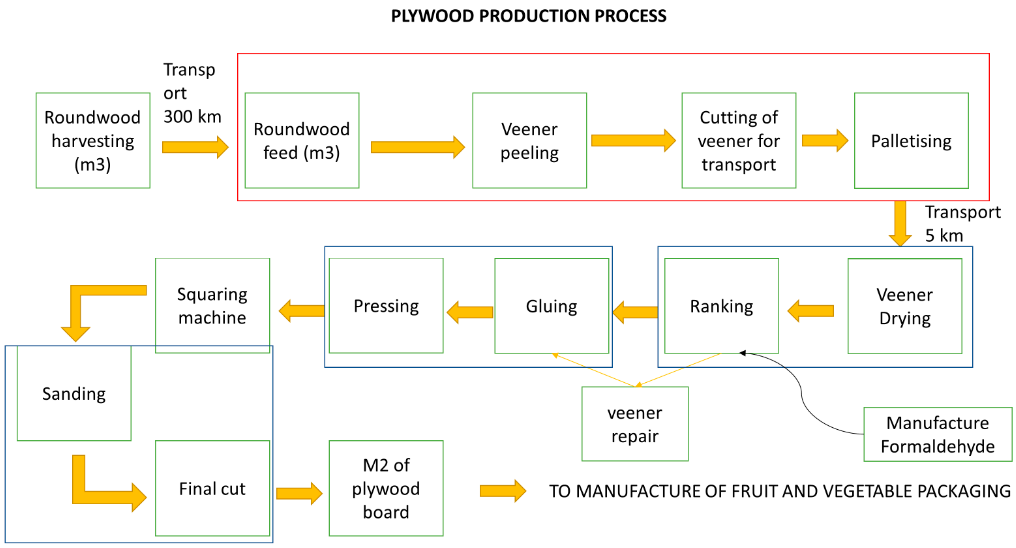

Figure 9. Flow chart of plywood manufacturing processes.

Data were obtained from the ECOINVENT database for harvesting and supplying poplar roundwood, for the industrial manufacturing processes, the data were collected from three of the most important plywood mills in Spain.

Furthermore, slats are pieces of solid wood, generally sawn from several pine species. The slats are manufactured from pieces of sawn wood with a quadrangular section by mitring (a diagonal section that divides the slats into two pieces of triangular section). The slats are intended for the corners (boards) in the WB (see Figure 2). To obtain these pieces, the roundwood passes through a sawmill that follows the industrial transformation processes shown in Figure 10. The information on all slat production processes has been obtained from the ECOINVENT database on softwood-sawn timber products.

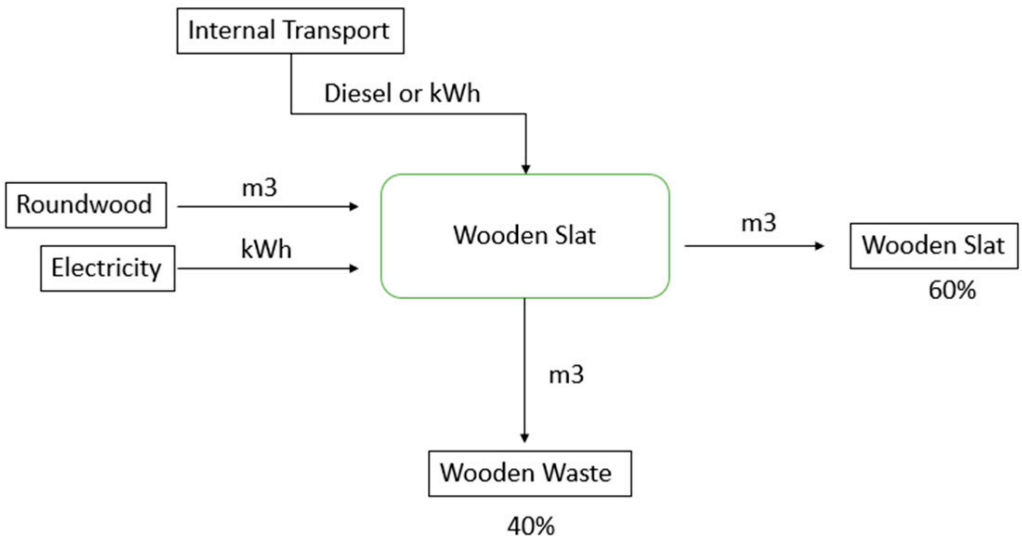

Figure 10. Unit process of wooden slat production.

Finally, Figure 11 shows a general diagram of the unit processes in the manufacture of Pitufo®, including the transport of the material to the WB manufacturing factory and the internal logistics.

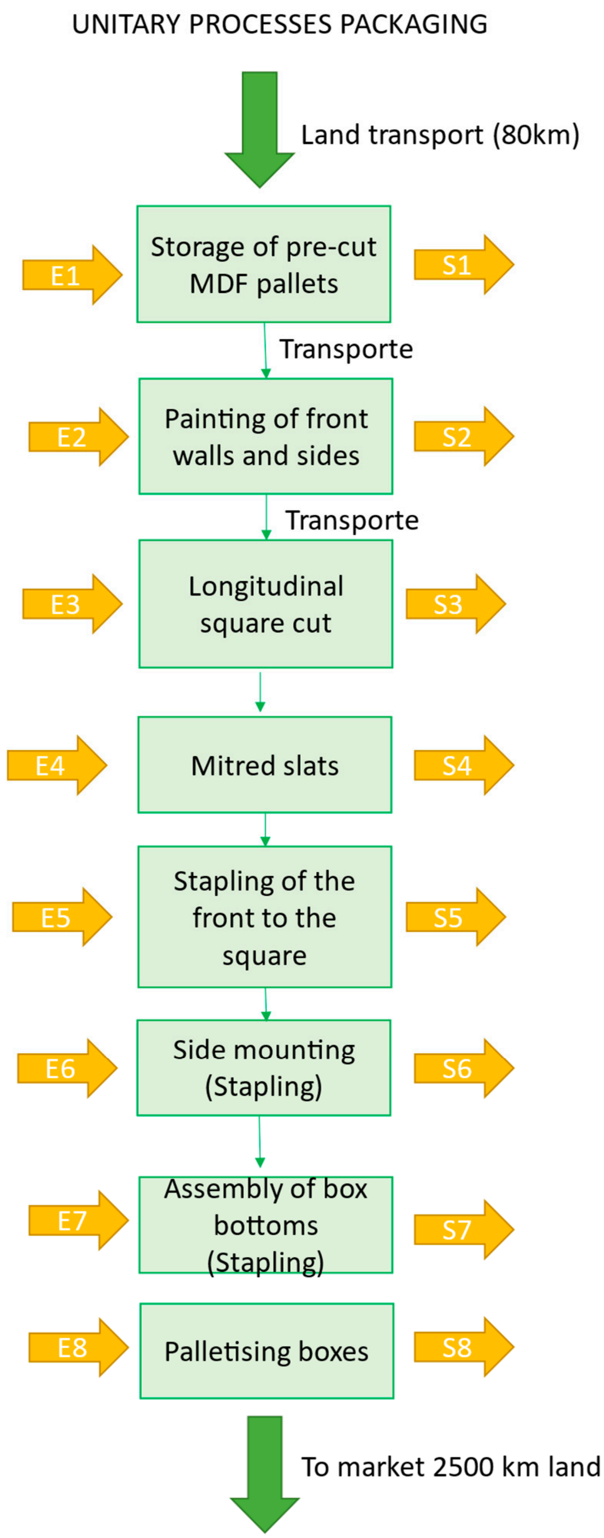

Figure 11. Flow chart of Pitufo® production.

Transport of the materials to the factory is generally carried out in 24 t trucks. Table 3 describes the average distances travelled by the various input materials to the WB assembly factory, adapting the units firstly to tkm per package and then to tkm per FU.

Internal transport and logistics refer to all movements carried out with forklifts within the production facilities. This transport is carried out using electric or diesel forklift trucks with a load capacity of up to 1500 kg, with electric forklift trucks being the most common (Figure 12). These trucks operate fully loaded, and each trip lasts, on average, about 60 s. (Table 4).

Table 3. Transport allocations of the different materials for each Pitufo® and for the total functional unit.

	Average Distance (km)	Load (t)	Involvement by Pitufo® (tkm)	Involvement Functional Unit (tkm)
Slats transport	138	24	0.017388	7560
Plywood transport	80	24	0.00621	2700
MDF treated transport	80	24	0.008004	3480
Roundwood transport	300	24	0.052923	23,010
Transport Galvanised steel clamps	14	24	9.2×10^{-5}	40
Paint transport	68	24	Not considered	Not considered
MDF transport	600	24	0.06003	26,100

Figure 12. Internal transport unitary process.

Table 4. Analysis of the vehicles used for the internal transport of material in the sector industries.

	Diesel Forklift	Electric Forklift
Maximum load capacity	1500	
Full load power	2.3 l/h	4.1 kW
Activity time(s)	60	60
Source of information for the environmental damage model	ECOINVENT v3.01	OECD/IEA 2015

The inputs and outputs of the unitary processes have been grouped into two essential phases, which are shown in the following Figure 13, which correspond to the two main processes of the assembly line in the factory:

- Unitary process for the painting of fronts and sides;
- Unit assembly process of the WB.

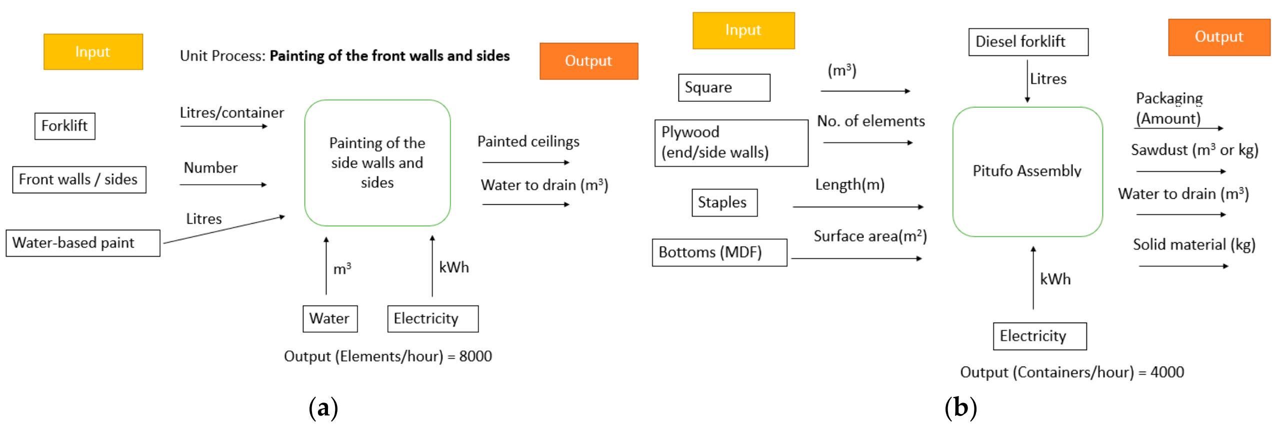

Figure 13. Inputs and outputs of: (**a**) painting unitary process. (**b**) Pitufo® assembly unitary process.

For the painting of fronts and sides, which are already pre-cut to size in previous processes, the material input is considered by some elements, as previous unitary processes determine it.

Each truck transports 26,208 Pitufos®, which means a total load weight of 6.7 t, and the 26 pallets, which at a weight of 20 kg per pallet, give a total of 520 kg per pallet. Therefore, each truck transports a total of 7.2 tonnes. So, for the inventory of this phase, we obtain the following calculation:

$$\text{Transport load} \times \text{Number of travels (functional unit/travel load)} \times \text{distance} = 7.2 \times 17 \times 50 = 6120 \text{ tkm}$$

Lastly, the end-of-life inventory of the Pitufos® is carried out. As the German target market for this study is responsible for managing packaging waste, the EUROSTAT database was consulted to determine the different treatments applied to wooden packaging in this country. A comparison has also been made with the treatments carried out in Spain to allocate these charges to the packaging waste at the place of production (see Table 5).

Table 5. End-of-life treatments applied to wood packaging according to the country of production. Source: EUROSTAT.

Country	Germany	Spain
Energy recovery	68.4%	26.7%
Non-energy recovery	0%	0%
Recycling of materials	31.6%	54.0%
Other forms of recycling (including composting)	0%	0%
Unknown	0%	19.3%
Total	100%	100%

2.4.2. Inventory Analysis of CCBs

The CCB cycle begins with manufacturing the raw materials for its production. Corrugated board is made from different types of paper: either paper made mainly from virgin wood fibres (*kraft liners* from mainly sulphate or Kraft processes for the production of cellulosic pulp or paper made mainly from recycled fibres (*test liners* and *flutings*)) [24]

Corrugated base papers comprise Europe's most significant share of paper and board production, accounting for 37% of total paper and board production [25]. The EU production of corrugated base papers in 2020 was 30.1 million tonnes. A total of 88% of corrugated packaging is increasingly derived from recycled content and has a recycling utilisation rate already reaching almost 90% (see Table 6).

Table 6. Summary of base paper used for corrugated cardboard production in 2020 [26].

Material	Millions of Tons	Fibre Composition	
	Total	Primary	Recycled
Kraftliner	4.4	3.2	1.2
Testliner	12.5		12.5
Another *recycled liner* (Schrenz)	1.0		1.0
***Fluting* semi-chemical**	0.6	0.5	0.1
***Fluting* recycling**	11.6		11.6
TOTAL	30.1	3.7	26.4
Percentage		12%	88%

As described in other studies [27], the paper reels are transported to the industry responsible for producing cardboard sheets and boxes. The paper reels of *liners* and *flutings* with 100% recycled fibre are transported by road in 40 t trucks with an average distance of 220 km.

The composition of the cardboard changes depending on the size and strength of the cardboard. For the equivalent CCB, the following representative composition is used:

- Outer layer: *Testliner*, 100% recycled fibre, weighing 195 g/m^2.
- Corrugated outer: *Fluting*, 100% recycled fibre, weighing 170 g/m^2.
- Middle layer: *Fluting*, 100% recycled fibre, weighing 170 g/m^2.
- Inside: *Fluting*, 100% recycled fibre, weighing 190 g/m^2.
- Inner layer: *Testliner*, 100% recycled fibre, weighing 250 g/m^2.

Based on information obtained by manufacturers in the corrugated board manufacturing process, a loss percentage of 10% is considered due to cuts in the sheet. Energy consumption data for the manufacturing process, die-cutting and manufacturing losses have been obtained from [24]. Screen printing inks (water-based) and adhesives (composed of starch, caustic soda, borax and anti-wetting agents) used to bind the paper types making up the sheet have been excluded as they account for less than 1% inks and 2% adhesives of the total mass of raw materials for a CCB.

CCBs are generally not transported assembled to the product packer. The CCB manufacturer die-cuts the cardboard sheets and leaves them ready to be assembled at the packaging factory, thus reducing transport costs, as they are shipped on flat-packed pallets. Once the sheets have been die-cut, they are transported to the packaging centres. A truck transports around 60,000 sheets for the CCB manufacture, equivalent to 60,000 CCB units. To transport 1000 tonnes of product, 434,783 sheets are required, plus an additional 0.1% for losses or breakages. This transport is carried out in 40 t non-refrigerated trucks over an average distance of 100 km. Therefore, a total of 8 trucks of 40 t will be considered for the transport of the required sheets.

When packing, strapping and palletising the new containers, the pallets are reused, and the amount of polystyrene film used is less than 2% of the weight of the raw material, so it has been excluded from the study. Likewise, the operations carried out in the fruit and vegetable warehouses are also excluded, simply counting the assembly of the CCB, as this operation is directly related to the type of packaging. In contrast, the rest of the operations are common to both types of packaging.

For internal transport within the industrial facilities, i.e., the movement of forklifts, average data and the number of sheets per pallet were considered. Specifically, it has been considered that these forklifts have a load capacity of up to 1,500 kg, with average movements lasting approximately 60 s. After estimations with CCB manufacturers, two types of forklifts were defined: electric forklifts (67%) and diesel-powered forklifts (33%).

As WBs, CCBs are single-use containers, according to RD 888/1988 [28]. Thus, the end-of-life stage consists of transporting used boxes to waste management centres and waste treatment processes. When the CCBs break or are no longer useful and the cardboard from the die-cutting of the sheets is lost, they are transported to the waste management centres in 16 t lorries located at an average distance of 50 km. All boxes required for the transport of the product are managed in the country of destination (Germany), and boxes and sheets that are broken during assembly and manufacture are managed in the country of origin (Spain).

The data on end-of-life management treatments of CCB waste have been extracted from the EUROSTAT database [29]. Table 7 describes the percentage distribution of paper and board waste destinations according to their treatment for Spain and Germany.

Table 7. Percentage distribution of treatments applied to cardboard packaging waste by country. Source: EUROSTAT.

Destination	Country	
	Germany	Spain
Incineration/energy recovery	12.28%	0%
Non-energy recovery	0%	0%
Incineration with energy recovery in waste incinerators	0.03%	5.38%
Recycling of materials	87.33%	94.62%
Other forms of recycling (including composting)	0.36%	0%
Total	100%	100%

3. Results and Discussion

Once the inventory analyses of the functional units have been carried out, the WBs' impacts are assessed using the methodology and impact categories described in Section 2.3.

3.1. Impact Assessment

The impacts assessment evaluates the potential environmental impacts associated with the inputs and outputs identified during the inventory analysis.

3.1.1. Global Warming Potential

This category assesses the total GHG emitted during the product's life cycle, measured in CO_2 eq.

Figure 14 shows the contribution of the different processes to the impact categories. The results show that the main processes contributing to global warming potential are first the electrical consumption of the WB manufacturing machinery (11% of total CO_2 eq. emissions), followed by the steel used to staple the Pitufo® (8%) and the ammonia used in the manufacture of Urea-Formaldehyde (UF) as an adhesive for the different wood-based panels, both in plywood and MDF (14%). The remaining processes refer to a comprehensive set of processes that individually contribute less than 0.1% each.

3.1.2. Terrestrial Acidification

This environmental impact category assesses the contribution to soil and water acidification, mainly due to the emission of acidic substances. The impact is measured in SO_{2eq}. Terrestrial acidification is defined as the loss of the neutralising capacity of soil and water, which occurs because of sulphur oxides and nitrogen returning to the earth's surface in the form of acids. The calculation of terrestrial acidification is mainly based on the studies of [30–33]. To understand the process of terrestrial acidification in soil and water, it must be considered that NO_x, NH_3 or SO_2 emissions follow the atmospheric fate before being deposited in the soil. Subsequently, these emissions are leached into the soil by changing the concentration of protons (H^+) of the aqueous solution in the soil. This change in acidity or lowering of pH in soil and water can affect plant species, both agricultural and forest [34].

Figure 14 shows the main results obtained. Thus, the process with the most significant impact is the production of electricity in coal-fired thermal power plants, with 22% of total SO_{2eq} emissions. These emissions are due to the electricity mix for the year being analysed in Spain as a whole and to the fact that coal is a fossil fuel that contains sulphur, which means that, in the combustion reaction, sulphur oxides are produced and emitted into the atmosphere. This process is followed in importance by the manufacture of MDF (14%) due to its UF content, which requires ammonia (NH_3). Ammonia emissions directly contribute to soil acidification [35].

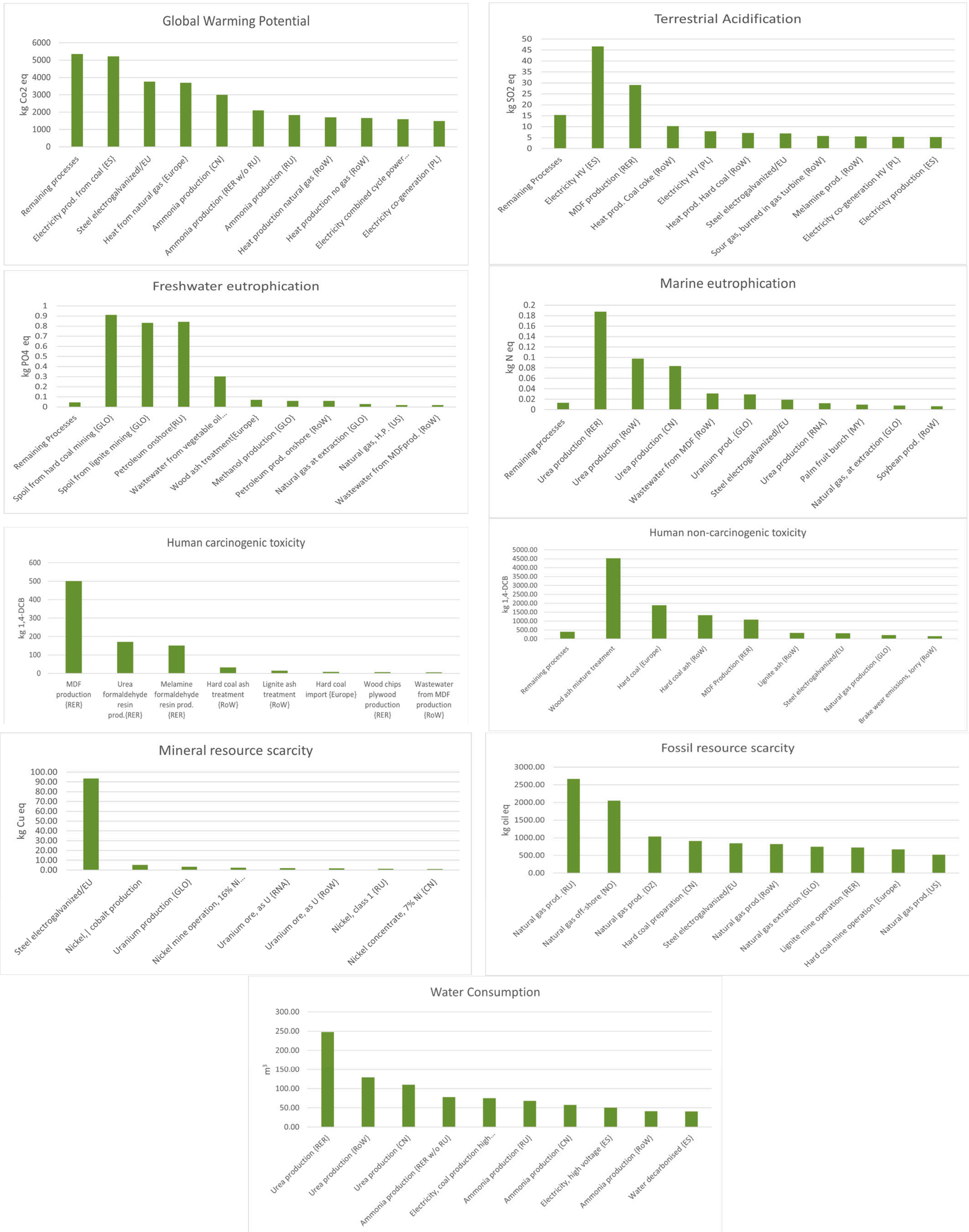

Figure 14. Contribution from inventory to different impact categories.

3.1.3. Freshwater Eutrophication

This environmental impact category looks at the release of nutrients into the environment, which can lead to excessive algal and plant growth, particularly negatively affecting aquatic ecosystems [36]. The impact is measured in PO_4 eq. Water eutrophication is caused by the discharge of nutrients into soil or freshwater bodies with a consequent increase in nutrient levels, i.e., phosphorus and nitrogen. The environmental impacts related to freshwater eutrophication are numerous, following a sequence of ecological impacts in which the number of nutrients in the water increases, which increases their uptake by autotrophic organisms such as cyanobacteria and algae, followed by heterotrophic species such as fish and invertebrates [37]. Finally, this leads to a relative loss of biodiversity of flora species and, consequently, of fauna [38].

Figure 14 shows the main results obtained in this study for the WB. The impact on water eutrophication is low, and the processes that contribute most are the remains of mining activities (with 78% of the total PO_4 eq.) and ash from wood combustion (2%), but always at shallow values.

3.1.4. Marine Eutrophication

Eutrophication is a form of marine pollution that occurs when excess nutrients enter aquatic ecosystems, inducing habitat changes due to this nutrient shift [39]. Eutrophication is expressed in kg N eq. Marine eutrophication occurs due to runoff and leaching of plant nutrients from the soil and their discharge into river or marine systems. In the case of marine water, unlike the former, nitrogen is the limiting nutrient in marine waters [40]. The increase in nutrients in marine waters points to several impacts on marine ecosystems, such as the depletion of benthic oxygen, leading to hypoxic waters [41]. In extreme excess cases, it can even lead to anoxia, one of the most severe and widespread causes of disturbance to marine ecosystems [42].

The results of evaluating this category for WBs' impact are shown in Figure 14. Marine eutrophication has a minimal impact, whereas the processes that can contribute the most are those in which nitrogen-containing compounds are used, such as the manufacture of UF glue and other processes, which need to be analysed in detail due to their shallow impact.

3.1.5. Human Toxicity

Human toxicity and ecotoxicity account for environmental persistence (fate), accumulation in the human food chain (exposure), and toxicity (effect) of a chemical. Toxicity potential is expressed in kg 1,4-dichlorobenzene equivalents (1,4 DCB eq.). It is often classified into human toxicity impacts that can lead to carcinogenic and non-carcinogenic conditions.

In terms of the carcinogenicity of a substance, all substances with a carcinogenic effective dose ED_{50} (the dose that produces the effect in 50% of the population) are considered as necessarily carcinogenic to humans [43]. IARC [44] gives a list of substances distributed in groups of the probability of causing cancerous diseases. In this classification, the different groups of substances analysed are:

- Group 1: carcinogenic to humans.
- Group 2A: probably carcinogenic to humans.
- Group 2B: possibly carcinogenic to humans.
- Group 3: cannot be classified as carcinogenic to humans.

Figure 14 shows the results obtained in this study for WBs. The level of 1,4DCB eq. is practically negligible. However, it should be noted that the primary emissions occur when manufacturing the MDF and mixing and applying the UF glue, as wood dust and formaldehyde belong to group one of cancer-causing substances in humans [45]. That is why sufficient preventive measures are in place in woodworking industries that do not allow direct contact with these substances. Therefore, dust from sanding (e.g., in finishing MDFs and plywood) is removed by extractors, and adhesives are applied with appropriate safety measures for the workers.

The non-carcinogenic toxicity considers the toxicity to humans of substances that are not strictly carcinogenic and are produced in processes (e.g., heavy metals) but are toxic and can cause other illnesses [46].

Figure 14 shows the results for WBs. The values obtained are extremely low or negligible. Thus, the processes that influence non-carcinogenic toxicity are the landfill deposition treatments of coal ash and ashes derived from the combustion/biodegradation of wood and bark, accounting for almost 80% of the weight within this impact category.

3.1.6. Depletion of Abiotic Resources

This considers the depletion of mineral resources and fossil fuels consumed during the life cycle of the FU analysed. To analyse this impact category, both the impact of the scarcity of mineral resources and the depletion of fossil resources are considered.

The mineral resource scarcity expresses the average extra amount of ore that will be produced in the future due to the extraction of 1 kg of a mineral resource and is expressed in kilograms of copper equivalent (kg CU eq.) [47]. Figure 14 shows the results. The contribution of the WBs to the scarcity of mineral resources is almost entirely due to the manufacture of staples for the stapling of galvanised steel, with more than 90% of the total.

Moreover, fossil resource scarcity is the depletion of fossil resources expressed in kilograms of crude oil equivalent (kBOE or kilo barrel of oil equivalent). It considers the consumption of fossil fuels in the processes. Figure 14 shows that electricity production using natural gas (32% of the total) is the main contribution, followed by manufacturing ammonia, which is necessary for gluing wood-based panels (plywood and MDF).

3.1.7. Water Consumption

This impact category considers the water consumption in all manufacturing processes. Figure 14 shows the results. The process with the most significant contribution is the manufacture of the UF glues specifically, which accounts for almost 41%, but also the rest of the processes necessary for the manufacture of the adhesive, such as ammonia.

3.2. Discussion

Table 8 summarises all the results obtained from the LCA of WBs compared to CCBs for the analysed functional unit, with a comparison of the different categories depending on the packaging.

Table 8. Results of mid-term impact categories.

Impact Category	Pitufo® (WB)	Cardboard Packaging (CCB)
Global Warming Potential (kgCO_2 eq.)	48,828.33	99,649.65
Terrestrial acidification (kgSO_2 eq.)	210.11	308.99
Eutrophication of water (kg P eq.)	3.22	14.00
Marine eutrophication (kg N eq.)	0.58	11.60
Carcinogenic human toxicity (kg 1,4 DCB)	936.48	917.75
Non-carcinogenic human toxicity (kg 1,4 DCB)	11,644.26	23,288.52
Mineral resource scarcity (kg Cu eq.)	115.11	93.24
Fossil resource depletion (kg oil eq.)	18,393.07	27,868.29
Water Consumption (m^3)	1192.74	1403.22

The study highlights significant differences in their sustainability profiles. In most categories, WBs exhibit a lower environmental impact, making them the more environmentally friendly option.

In most categories, the WB exhibits a lower environmental impact. In **global warming potential**, the WB shows an impact of 48,828 kg CO_2 eq., significantly lower than the 99,649 kg CO_2 eq. for the CCB; this substantial difference is largely due to the higher energy consumption required for recycling paper and cardboard. Similarly, the WB outperforms the CCB in **terrestrial acidification**, with impacts of 210 kg SO_2 eq. and 309 kg SO_2 eq., respectively, reflecting the extensive chemical use in the CCB recycling processes. For **freshwater and marine eutrophication**, the WB presents 3.2 kg P eq. in freshwater and 0.58 kg P eq. in the marine environment, compared to 14 kg P eq. of the CCB in freshwater and 11.6 kg N eq. Thus, in both cases, the impact is significantly higher for the CCB than for the WB, mainly due to the use of chemicals necessary for recycling paper and cardboard. **The non-carcinogenic human toxicity** is 11,644 kg 1,4 CDB for the WB, compared to 23,288 kg 1,4 CDB for the CCB. CCBs have a significantly higher environmental impact than WBs due to the use of chemicals in the recycling of paper and cardboard and the higher energy consumption from fossil fuels. The **depletion of fossil resources** is 18,393 kg oil eq. for the WB, compared to 27,878 kg oil eq. for the CCB. This category is also marked by a higher impact of the CCB than the WB due to the higher energy consumption in paper and cardboard recycling and manufacturing processes. **The water consumption** is 1192 m^3 for the WB, compared to 1403 m^3 for the CCB. This category is also marked by a higher impact of the CCB than the WB due to the higher water consumption in paper and cardboard recycling and manufacturing processes.

In summary, the major impact of CCBs on the environmental categories named above is mainly due to the higher energy consumption, and higher chemical and water use of the cardboard recycling process.

On the other hand, the WB has slightly higher impacts in a few categories. **The carcinogenic human toxicity** is 936 kg 1,4 DCB for the WB, compared to 917 kg 1,4 DCB for the CCB. Although the levels are very low for both types of packaging, the WB has a higher impact in this category, although the difference is not significant, varying between 2 and 3% of the packaging. This is mainly due to adhesive resins in the wood material (MDFs and plywood) composed of UF. The **scarcity of mineral resources** for the functional unit analysed is 115 kg Cu eq. for the WB, compared to 93 kg Cu eq. for the CCB. Although the levels are very low for both types of packaging, the WB has a slightly higher impact. This is almost exclusively due to the use of steel as staples in the WB.

Other studies assessing the environmental impact of different types of boxes reached conclusions similar to our study. Del Borghi et al. [48] used the LCA approach to compare the impact of reusable plastic crates, wooden boxes and cardboard boxes for food transport, and one of their conclusions was that wooden boxes have less environmental impact than cardboard boxes, mainly due to the consumption of chemicals in the recycling process and the higher energy consumption of chemicals in the manufacturing and recycling processes. Accorsi et al. [49] compared the economic and environmental impact of single-use boxes (wooden and cardboard) with reusable plastic crates in different scenarios and the study shows that wooden boxes are better than cardboard in terms of environmental impact. These articles, which are more recent, coincide with other older research papers that have also conducted LCAs on the different packaging materials [5,6,10,17], which also show that WBs are better for the environment than CCBs, although it should be noted that in none of the existing LCAs was the main objective to compare two single-use packages; the main objective and research were focused on comparing single-use packaging vs. reusable plastic packaging.

Characterisation

Characterisation is the stage of the LCA in which the results are assigned to the different environmental impact categories. This stage involves the quantification and assessment of the input and output flows associated with the system under study, and the assignment of these to the relevant impact categories. This process is based on specific characterisation factors, which are used to convert the quantities of input and output flows into a common unit for each impact category. The graphical representation of the comparative characterisation results between the WBs and the CCBs is presented in Figure 15.

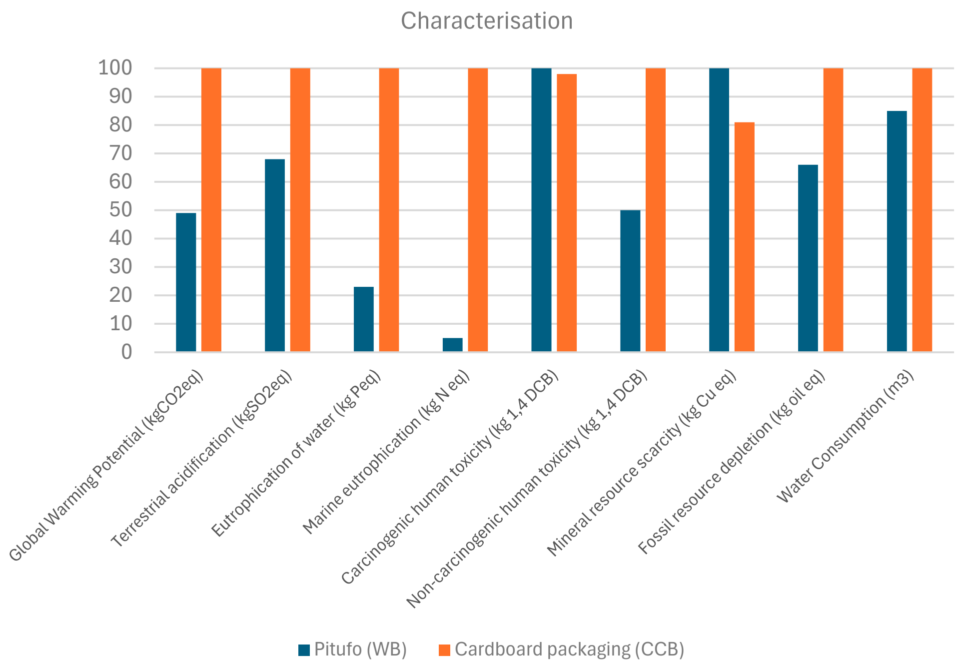

Figure 15. Characterisation of the results.

4. Conclusions

For the sustainability impact evaluation and monitoring, the Life Cycle Analysis (LCA) following ISO 14040:2006 and ISO 14044:2006 has assessed each phase of the process, from the harvesting and supplying of raw materials to the end of the packaging's useful life, highlighting the main impacts of global warming potential, terrestrial acidification, eutrophication and human toxicity. The representative selected packaging is a wooden box (WB) Pitufo® of 2 kg load. The functional unit for the study is the transport of 1000 t of mandarins from Spain to the German market at a distance of 2000 km using heavy trucks. The results indicate that the phases with the most significant impact are concentrated in producing electricity for manufacturing machinery and using urea-formaldehyde (UF) adhesives in MDF and plywood boards.

Regarding global warming potential, the most significant contribution comes from electricity consumption in manufacturing factories (11%) and the steel used to staple the box parts (8%). Terrestrial acidification is mainly influenced by power generation (22%) and MDF production (14%) due to the use of ammonia. In freshwater eutrophication, mining waste and ash from wood combustion are the most significant contributors, although at very low levels. For mineral resource scarcity, steel staples account for more than 90% of the impact, while in fossil resource consumption, natural gas production and electricity generated from fossil fuels are the main drivers. Water consumption is dominated by the manufacture of UF adhesives, which accounts for 41% of the total.

As for the comparison between the WB and the corresponding corrugated cardboard box (CCB), the study concludes that the environmental impact of the CCB is significantly higher in most of the environmental impact categories assessed. The CCB has a higher global warming potential impact (99,649 kg CO_2 eq for CCB versus 48,828 kg CO_2 eq. for WB). Similarly, in categories such as terrestrial acidification and eutrophication in freshwater and marine environments, the CCB has a higher environmental footprint mainly due to using chemicals and energy consumption in its recycling and manufacturing process.

As a general conclusion of our research, wood-based packaging has a lower overall environmental impact than corrugated cardboard packaging, especially in the key impact criteria as global warming potential, acidification, eutrophication, human non-carcinogenic toxicity, fossil resource depletion and water consumption. Thus, the environmental analysis developed in this study has demonstrated the advantages of wood as the most sustainable material for fruit and vegetable packaging, transport and logistics.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A. Results of Critical Review

The use of results of the LCA study to support comparative assertions requires a critical review since their application is likely to affect stakeholders outside the LCA. As it is a comparative analysis between several products that fulfil the same function, if the public dissemination of the study is desired, the Section 6 of the ISO 14044:2006 requires the performance of a critical review by a panel of experts.

This study has been reviewed by a panel of experts, fulfilling the requirements established by the standards cited in this section.

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