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CARBON FOOTPRINT OF WOODEN AND PLASTIC PALLETS: A QUANTIFICATION WITH DIFFERENT SOFTWARE TOOLS

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ABSTRACT

Transport is one of the activities that generates the highest CO_2eq emissions. In the particular case of Chile, it is the second economic activity that generates the greatest environmental impact. The safe and efficient transport of products in domestic and foreign markets is often carried out with the help of pallets made of various materials, such as wood or plastic, which goes hand in hand with different environmental performance in their production. That is why it is important to know the carbon footprint of these products. The objectives of this study are to compare the value of the carbon footprint generated by the local production of wooden and plastic pallets and to evaluate the variations in its quantification using different software. For this purpose, the Chilean market is taken as a reference. This study follows the main guidelines of ISO 14040 and ISO 14067 standards as a reference framework. The functional unit is 1 pallet produced and the system boundary is from cradle to gate. The results show that wood and plastic pallets have an average carbon footprint of 4,12 kg CO_2eq and 38,85 kg CO_2eq respectively. The difference between the two pallets is mainly due to the environmental load of the raw materials. The causes of the variation in the estimation of the carbon footprint with different software are specifically based on the databases with which they can work. The ratio of 1:9 between the carbon footprint of wooden pallets concerning plastic pallets provides important data for decision making.

Keywords: Carbon footprint, materials, free software, life cycle assessment, plastic pallets, wooden pallets.

INTRODUCTION

The increase in export activities has demanded a series of inputs for its realization, being pallets one of the basic components in a country's internal and external supply chain. Pallets are a common unitary loading platform in the world and allow the safe and efficient handling, storage, transportation, loading, and unloading of goods. Currently, their high demand in exports has required exploring new materials for their manufacture, which goes hand in hand with heterogeneity of environmental impacts in their production. For example, the growing demand for these products has increased the extraction of raw materials to maintain and satisfy market requirements, increasing greenhouse gas (GHG) emissions due to the long distances involved in transporting the products. Thus, it is possible to find pallets made of wood (traditional), plastic, fiberglass, and combinations of raw materials such as wood-plastic (Hassanzadeh-Amin *et al*. 2018, Kočí 2019, Qiang *et al.* 2019, Anil *et al.* 2020, Khan *et al.* 2021).

Globally, the demand for pallets exceeded 5 billion units in 2017 to supply North American, Pacific Asia, and Western European markets and by 2024 the demand for pallets is expected to reach 5,8 billion units due to an increase in demand of 3,7 % per year (Freedonia 2021). Wood will remain the dominant material, but plastic, metal, and cardboard pallets will grow faster and gain market share (Freedonia 2021). According to CENEM (2017), in Chile pallets accounted for 65 % of the production of the packaging sector (85 % for export and 15 % for domestic use), which has responded directly to the effects of the slight increase in fruit exports. Pallets for domestic use showed a slight increase, mainly due to retail demand. Similarly, there was a certain continuity in demand from the meat, wine, and manufacturing sectors, which was also favorable for this segment.

The quantification of environmental impacts can be based on Life Cycle Analysis (LCA) which is a collection and analysis of input and output data of a system (product, process, or service) to measure different environmental impacts throughout its life cycle (cradle to grave) (Ihobe S.A. 2009). One of these impacts is the global warming potential which is equivalent to the Carbon Footprint (CF) measured in kg CO_2 eq. The CF of a product is then, the sum of greenhouse gas (GHG) emissions and GHG removals in a product system that is expressed through a single impact category of climate change (ISO 2018).

In this sense, some research has reported that wooden pallets present better environmental performance than plastic pallets (Deviatkin *et al*. 2019, Kočí 2019; Anil *et al*. 2020). However, the greater magnitude and variability in the results reported in other countries and continents for plastic pallets compared to wooden pallets has motivated us to determine the magnitudes of CF in pallets marketed in Chile. The CF analysis of wooden and plastic pallets allows producers to seek ways to reduce the environmental load of the product by knowing the hotspots that contribute most to the generation of this environmental impact, looking for the substitution of some raw materials, or changing technology, among other actions. In addition, products with better environmental performance are more sought after by consumers in developed countries, who are more environmentally conscious and interested in acquiring products with the best production practices in their value chain (Nekmahmud and Fekete-Farkas 2020, Kumar *et al.* 2021).

Currently, there are many software tools to measure the global warming potential based on the determination of the carbon footprint (Ormazabal *et al.* 2014, Peter *et al.* 2017). This information is being increasingly required by manufacturing companies, which can implement improvements in manufacturing, generating more environmentally friendly products for increasingly demanding and environmentally conscious consumers, who demand access to information at the time of purchase.

The use of software for the simulation of processes and the calculation of CF measured in kg CO_2 eq constitutes an important data for decision makers, having as an alternative the use of electronic spreadsheets that makes it much more complex and time-consuming to obtain the data when considering the environmental dimension of the product.

The use of software for the assessment of the environmental impact could generate different results, as reported by some researchers (Lopes Silva *et al.* 2019, Pauer *et al.* 2020). According to Lopes Silva *et al.* (2019), the main software for LCA development, which reports various environmental impacts, including CF, are SimaPro (Pre-sustainability 2021), Gabi (Pauer *et al.* 2020), Umberto (Lopes Silva *et al.* 2019), and OpenLCA (Ciroth 2007). To date, no free software has been used to compare the environmental impact of pallets of different materials.

Based on the above, this article aims to compare the CF generated by the manufacture of wood and plastic pallets using an LCA approach, to identify the processes that contribute most to CF and thus propose ways to reduce them. The secondary objectives of this work are to evaluate the CF with freely available LCA tools, analyze the causes that originate variation in its quantification, and propose solutions so that decision making is not affected by the use of the tools. For this purpose, a case study of the Chilean market is used.

MATERIALS AND METHODS

This article assesses the carbon footprint using the LCA methodology and the main guidelines of ISO 14040 (ISO 2006) and ISO 14067 (ISO 2018) standards as a reference framework, except for the latest updates of the characterization factors, due to limitations of the databases to which access is available in free software. In this context, the following section is structured in 4 phases: (1) case studies; (2) definition of the objective and scope; (3) life cycle inventory analysis; (4) carbon footprint assessment using free and licensed software.

Case studies

In the case of the wooden pallet, the information was obtained from Gajardo (2020) and is based on primary source data obtained from the company Pallets WIA. This company is located in Santiago, Chile, and specializes in designing, manufacturing, repairing, maintaining, and distributing various types of pallets (Palletwia 2020). Pallet WIA's main product is the standard pine-wood pallet (120 cm x 100 cm), with a variable monthly production of up to 10000 pallets per month (personal communication). The pallet produced supplies the local industry, especially the retail sector, and does not require sanitary treatment for use, unlike the pallet used to move export products, which requires sanitary treatment, such as heat treatment application or chemical compounds.

In the case of plastic pallets, the information was obtained from secondary sources. This is due to the difficulty of finding a company that provides plastic pallet production data in a national context. The data collected by Gajardo (2020), were based on four studies that were selected as the main base sources (Elduque *et al*. 2018, Córdoba Guerrero 2018, Kočí 2019, Anil *et al.* 2020).

Definition of objective and scope

The main objective of this study is to compare the CF of wooden pallets with plastic pallets. For this purpose, three freely available software, CCaLC2 (Azapagic 2016), GEMIS (Fritsche and Schmidt 2003), and OpenLCA (Ciroth 2007), and one licensed, SimaPro (Pre-sustainability 2021) is used. In this sense, a secondary objective is to identify the main similarities and differences between the software used, using the licensed software as a reference. The selection of the three open access software is based on their versatility to be applied in different economic sectors, while the licensed software will allow the analysis and comparison of the results.

To compare the CF generated by the wooden pallet and plastic pallet, a functional unit (FU) needs to be defined. In this study, the FU was 1 pallet of 1200 mm x 1000 mm, whose load capacity is 1500 kg, which its load capacity is in range of international standard. In this study, the FU is oriented to the production stage (not including distribution, use, and waste management, among others) of the pallet using new raw material in a Latin American case study. However, there are other investigations of pallets with different materiality, using reuse and recycling criteria, which define the FU according to the purpose for which it was manufactured - transport of goods by weight or distance (Deviatkin *et al*. 2019, Anil *et al*. 2020), resistance and lifespan (Khan *et al*. 2021), among others.

The system boundaries considered in this study were from "cradle to gate", including the extraction of raw materials, transport of raw materials and inputs, to the manufacture of the product. The process steps included in the CF evaluation differed depending on the manufacturing process of each type of pallet (wood or plastic).

Life cycle inventory analysis

Life cycle inventories for the production of wooden (Table 1) and plastic (Table 2) pallets were developed and brought to the FU, i.e., one pallet respectively. The stages considered for the wooden pallet manufacturing process were two: (I) raw material acquisition and (II) manufacturing.

Table 1: Inventory for the manufacture of 1 wooden pallet.

Input	**Unit**	**I) Raw Material Acquisition**		**II) Manufacturing**
Wood	kg	2,1E+01		
Steel	kg	4,9E-01		
Diesel used for maritime transport of nails import [a]	km	1,9E+04		-
Diesel used for land transport of nails import [b]	km	2,3E+02		-
Diesel used for land transport of nails purchase [c]	km	3,2E+01		-
Diesel used for land transport of lumber purchase [d]	km	5,1E+02		-
Liquefied gas	m^3	-		6,7E-05
Electricity based on diesel	MJ	-		1,2E-03
Electricity based on natural gas	MJ	-		4,4E-03
Electricity based on coal-fired	MJ	-		4,2E-02
Electricity based on hydroelectric power	MJ	-		4,2E-02
Electricity based on wind energy	MJ	-		1,5E-02
Electricity based on photovoltaic energy	MJ	-		1,5E-02

[a] Distance between the manufacturer's nearest port and the supplier's nearest port in Chile.
[b] Distance by land between the manufacturer and the nearest port, in conjunction with the distance between the port and the supplier's distribution center in Chile.
[c] Distance by land between the supplier in Chile and the pallet manufacturer.
[d] Distance between the lumber distribution center and the pallet manufacturer.

On the other hand, the stages considered for the plastic pallet manufacturing process were: (I) acquisition of raw materials; (II) melting and molding; (III) cooling.

Table 2: Inventory for the manufacturing of 1 plastic pallet.

Input	Unit	I) Raw material acquisition	II) Melting and molding	III) Cooling
HDPE Resin	kg	1,9E+01	-	-
Diesel used for land transport of resin purchase [a]	km	2,0E+01	-	-
Water	kg	-	1,7E+03	-
Electricity based on diesel	MJ	-	5,0E-03	2,5E-02
Electricity based on natural gas	MJ	-	3,3E-02	1,7E-01
Electricity based on coal-fired	MJ	-	4,7E-02	2,4E-01
Electricity based on hydroelectric power	MJ	-	4,7E-02	2,4E-01
Electricity based on wind energy	MJ	-	1,7E-02	8,5E-02
Electricity based on photovoltaic energy	MJ	-	1,7E-02	8,5E-02

[a] Ground distance between the supplier and the pallet manufacturer.

Carbon footprint assessment using free and licensed software tools

CCaLC2

CCaLC2 is the second generation of the CCaLC (Carbon Calculations over the Life Cycle of Industrial Activities) carbon footprint tool (Azapagic 2016). It was developed by the Sustainable Industrial System group based at the University of Manchester (The University of Manchester 2018). This software allows the assessment of six environmental impact categories: carbon footprint, water footprint, acidification potential, eutrophication potential, ozone depletion potential, photochemical smog potential, and human toxicity potential. According to direct communication with the authors of the software, these categories are evaluated following the CML 2001 methodology. This software has been developed to allow non-expert users to calculate various environmental impact categories quickly and easily, following internationally accepted LCA standards; reduce efforts related to data collection by delivering comprehensive databases; help find the greatest contributions from an environmental perspective, among other objectives (Azapagic 2016).

Since the development of the first version of the CCalC2 software (Azapagic 2016), its use has spread rapidly in scientific and non-scientific literature, in different economic sectors. As an example, in the agro-forestry sector, the work of Iriarte *et al.* (2014) and Whittaker *et al.* (2013) can be highlighted.

Gemis

GEMIS (Global Emissions Model for Integrated System) is a life cycle calculation software developed for companies and decision makers to model energy, material, and transport flows (Peter *et al.* 2017). GEMIS (Fritsche and Schmidt 2003) allows a life cycle assessment of a variety of emissions, resource use, and costs. GEMIS (Fritsche and Schmidt 2003) also allows aggregation of emissions in CO_2 eq, SO_2 eq, and tropospheric ozone precursor potential. The software has its own integrated database with various material production chains, processes, and transport services (public transport, freight, air transport). Some research conducted with GEMIS (Fritsche and Schmidt 2003) in the agroforestry sector are those reported by Jungmeier *et al.* (2003), Meyer-Aurich *et al.* (2016), Serradj *et al.* (2016), and Beccali *et al.* (2010).

OpenLCA

OpenLCA (Ciroth 2007) is a free open-source software widely known in the area of LCA, which allows the calculation of environmental impacts during the entire life cycle of a product or service. The software has been created by Ciroth (2007) and since then economic and social indicators have been incorporated, allowing to cover all three areas of sustainability (Ciroth 2021). OpenLCA (Ciroth 2007) allows the integration of a variety of databases in conjunction with various environmental impact assessment methods. Additionally, the software allows the creation of proprietary databases and impact methodologies. This makes OpenLCA (Ciroth 2007) highly flexible and adaptable to different production areas. Some research conducted with this software in the agroforestry sector are those reported by Herrera-Huerta *et al.* (2012), Hersh and Mirkouei (2019), Montalba *et al.* (2019).

SimaPro

SimaPro (Pre-sustainability 2021) is a professional and widely used software in the LCA area to assess environmental impacts during the entire life cycle of a product, process, or service. SimaPro has been developed and distributed by PRé Consultants since 1990 (Pre-sustainability 2021). The software allows the integration of multiple databases and environmental assessment using various methodologies. The software has multiple applications, such as sustainability reporting, carbon and water footprint assessment, product design, environmental product declaration, among others (SimaPro 2021). Some publications of research conducted with this software in the agro-forestry sector, have been reported by the following authors: Han *et al.* (2015); Vásquez *et al.* (2017), and Puettmann *et al.* (2020).

The CF was evaluated using the databases and methodologies available for each free software tools. Regarding databases, the modeled unit processes were obtained from free databases available in each software. Table 3 presents the processes used for CF evaluation of wooden and plastic pallets. This table also shows the databases from which the processes were extracted for each software.

Concerning the methodologies, in the CCalC2 software (Azapagic 2016), the environmental assessment methodology CML 2001, updated version 2015 was used (Guinée *et al.* 2002, CML 2016). In the GEMIS software (Fritsche and Schmidt 2003), the methodology based on IPCC (2013) reports was used to convert emissions to global warming potential or its equivalent in CF. In the OpenLCA software (Ciroth 2007), the PEF Environmental Footprint (Mid-point indicator) methodology was used. Finally, in the case of the SimaPro software (Pre-sustainability 2021), the CML 2001 methodology was used, updated version 2015 (Guinée *et al.* 2002, CML 2016).

Table 3: List of unit processes used for CF evaluation of wooden and plastic pallets.

Input	GEMIS process	OpenLCA process	CCaLC2 process	SimaPro process
Wooden pallet				
Wood	Wood manufacturing\sawn timber-techn.dried-spruce [d]	Softwood forestry, at forest, sustainable managed, per kg wood - EU-28+3 [e]	Wood, pine timber [d]	Sawnwood, softwood, raw {RoW} sawing, softwood | APOS, U [f]
Steel	Metal\steel-wire rod rolled coils-global-2005 [d]	Steel cold rolled coil, single route, at plant, blast furnace route, carbon steel – ROW [e]	Steel production, electric, low-allowed, RoW [g]	Steel, low-allowed {RoW} steel production, converter, low-alloyed | APOS, U [f]
Diesel used for maritime transport of nails import	Ship (ocean)-2010 (solid cargo-Panamax) [d]	Transoceanic ship, containers, consumption mix, to consumer, heavy fuel oil driven, cargo, 27500 dwt payload capacity, ocean going – GLO [e]	General cargo ship (average), UK [g]	Transport, freight, sea, transoceanic ship {GLO}| processing | APOS, U [f]
Diesel used for land transport of nails import	Truck diesel EU 2010 [d]	Articulated lorry transport, Total weight 28-32 t, mix Euro 0-5, consumption mix, to consumer, diesel driven, Euro 0 - 5 mix, cargo, 28 - 32t gross weight / 22t payload capacity - ROW w/o EU-28+3 [e]	Transport, lorry 16-32t, EURO 3 [g]	Transport, freight, lorry 16-32 metric ton, EURO3 {RoW} transport, freight, lorry 16-32 metric ton, EURO3 | APOS, U [f]
Diesel used for land transport of nails purchase	Truck diesel -<7,5t-DE-2005 [d]	Articulated lorry transport, Total weight <7.5 t, mix Euro 0-5, consumption mix, to consumer, diesel driven, Euro 0 - 5 mix, cargo, up to 7,5t gross weight / 3,3t payload capacity - ROW w/o EU-28+3 [e]	Van - diesel (average) up to 3.5t, UK [g]	Transport, freight, lorry 3.5-7.5 metric ton, EURO3 {RoW} transport, freight, lorry 3.5-7.5 metric ton, EURO3 | APOS, U [f]

Diesel used for land transport of lumber purchase	Truck diesel EU 2010 [d]	Articulated lorry transport, Total weight 28-32 t, mix Euro 0-5, consumption mix, to consumer, diesel driven, Euro 0 - 5 mix, cargo, 28 - 32t gross weight / 22t payload capacity - ROW w/o EU-28+3 [e]	Transport, lorry 16-32t, EURO 3 [g]	Transport, freight, lorry 16-32 metric ton, EURO3 {RoW} transport, freight, lorry 16-32 metric ton, EURO3 | APOS, U [f]
Liquefied gas	Not available [a]	Not available [a]	LPG (burned) [d]	Liquefied petroleum gas {RoW}| market for | APOS, U [f]
Electricity based on diesel	Dieselmotor-powerplant-Cribbean-2000 [d]	Not available [c]	Diesel (used in farm machinery) [d]	Electricity, high voltage {CL} production mix | APOS, U [f]
Electricity based on natural gas	Not available [b]	Electricity from natural gas, production mix, at power plant, AC, mix of direct and CHP, technology mix regarding firing and flue gas cleaning, 1kV - 60kV – RSA [e]	Natural Gas (burned) [d]	
Electricity based on coal-fired	Xtra-deep\coal-UK-2000 [d]	Electricity from hard coal, production mix, at power plant, AC, mix of direct and CHP, technology mix regarding firing and flue gas cleaning, 1kV - 60kV – RSA [e]	Coal (electricity generation) (burned) [d]	
Electricity based on hydroelectric power	Hydro-powerplant-CZ-large [d]	Electricity from hydro power, production mix, at power plant, AC, technology mix of run-off-river, storage and pump storage, 1kV - 60kV – RSA [e]	Electricity – hydro [d]	

Electricity based on wind energy	Wind-park-medium-DE-2000 [d]	Electricity from wind power, production mix, at plant, AC, technology mix of onshore and offshore, 1kV - 60kV – RSA [e]	Electricity – wind [d]	
Electricity based on photovoltaic energy	Solar-PV-multi-CL-2015 [d]	Electricity from photovoltaic, production mix, at plant, AC, technology mix of CIS, CdTE, mono crystalline and multi crystalline, 1kV - 60kV [e]	Electricity - PV mix [d]	
Plastic pallet				
HDPE Resin	Chem-Orq\HDPE (from EcoInvent) [d]	HDPE granulates, production mix, at plant, Polymerisation of ethylene, 0,91- 0,96 g/cm^3, 28 g/mol per repeating unit [e]	Polyethylene, HDPE, granulate, at plant [g]	Polyethylene, high density, granulate {GLO} market for | APOS, U [f]
Diesel used for land transport of resin purchase	Truck diesel EU 2010 [d]	Articulated lorry transport, Total weight 28-32 t, mix Euro 0-5, consumption mix, to consumer, diesel driven, Euro 0 - 5 mix, cargo, 28 - 32t gross weight / 22t payload [e]	Transport, lorry 16-32t, EURO 3 [g]	Transport, freight, lorry 16-32 metric ton, EURO3 {RoW} transport, freight, lorry 16-32 metric ton, EURO3 | APOS, U [f]
Water	Xtra-drinking water\DE-2020 [d]	Water, completely softened, at user, technology mix, per kg water - EU-28+3 [e]	Water, completely softened at plant [g]	Water, completely softened, from decarbonized water, at user {RoW}| production | APOS, U [f]
Electricity based on diesel	Dieselmotor-powerplant-Cribbean-2000 [d]	Not available [c]	Diesel (used in farm machinery) [d]	Electricity, high voltage {CL} production mix | APOS, U [f]

Electricity based on natural gas	Not available [a]	Electricity from natural gas, production mix, at power plant, AC, mix of direct and CHP, technology mix regarding firing and flue gas cleaning, 1kV - 60kV – RSA [e]	Natural Gas (burned) [d]	
Electricity based on coal-fired	Xtra-deep\coal-UK-2000 [d]	Electricity from hard coal, production mix, at power plant, AC, mix of direct and CHP, technology mix regarding firing and flue gas cleaning, 1kV - 60kV – RSA [e]	Coal (electricity generation) (burned) [d]	
Electricity based on hydroelectric power	Hydro-powerplant-CZ-large [d]	Electricity from hydro power, production mix, at power plant, AC, technology mix of run-off-river, storage and pump storage, 1kV - 60kV – RSA [e]	Electricity – hydro [d]	
Electricity based on wind energy	Wind-park-medium-DE-2000 [d]	Electricity from wind power, production mix, at plant, AC, technology mix of onshore and offshore, 1kV - 60kV – RSA [e]	Electricity – wind [d]	
Electricity based on photovoltaic energy	Solar-PV-multi-CL-2015 [d]	Electricity from photovoltaic, production mix, at plant, AC, technology mix of CIS, CdTE, mono crystalline and multi crystalline, 1kV - 60kV [e]	Electricity - PV mix [d]	

[a] Emission factor was taken from EPA (2018)
[b] Emission factor was taken from BioGrace database (Neeft *et al.* 2015)
[c] Emission factor was taken from Agrybalise database (Wermielle and Colomb 2020)
[d] Taken from the Software's own database
[e] Taken from PEF Environmental Footprint database
[f] Take from Ecoinvent v.3.5 databases (Wernet *et al.* 2016)
[g] Take from Ecoinvent v.2.2 databases (Wernet *et al*. 2016) and from CCaLC2 software (Azapagic 2016)

RESULTS AND DISCUSION

To respond to the objectives of this study, the results of the determination of the carbon footprint of both pallets measured through different software are presented, together with the analysis of the causes that generate variation in the results.

Carbon footprint of the wooden pallet

The CF results of the wooden pallet and the contribution of the inputs to each stage are shown in Figure 1.

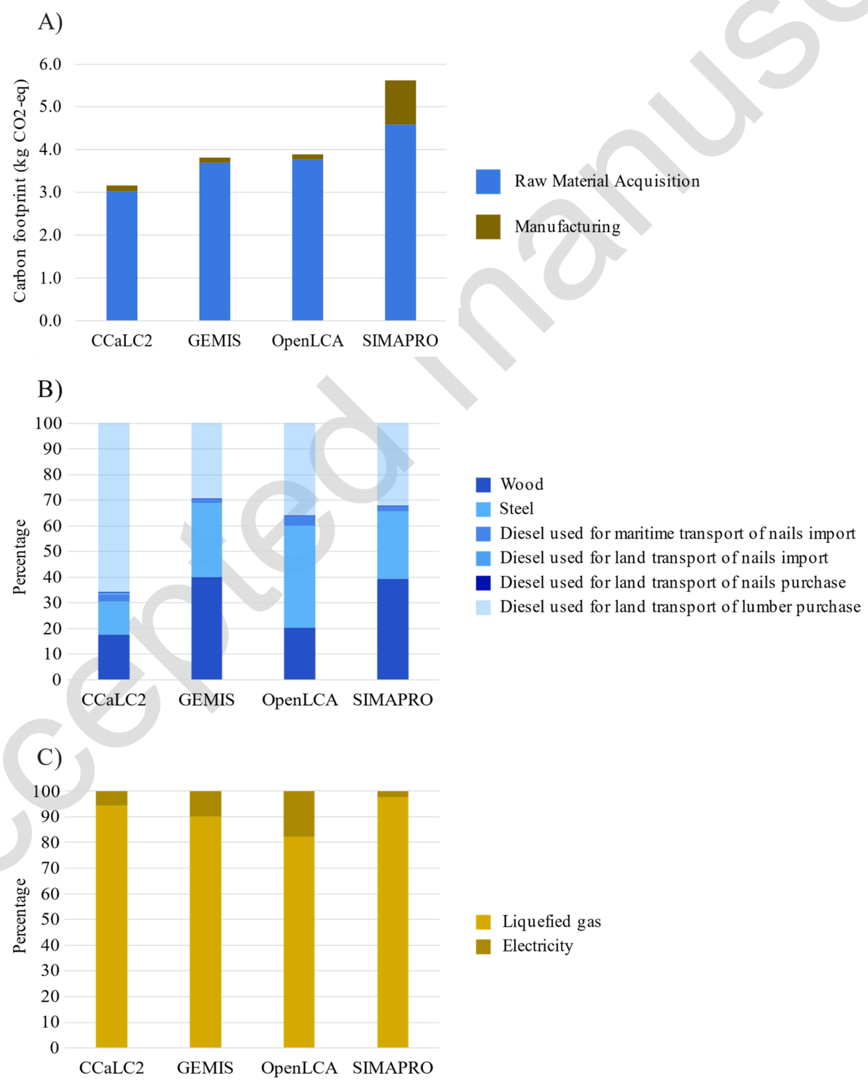

Figure 1: Total carbon footprint of the wooden pallet obtained by each software studied (A), and the percentage contribution of the process to raw material acquisition (B) and manufacturing (C).

Focusing on the total CF in each software, Figure 1 displays that the value of the CF range between 3,16 kg CO_2 eq (with CCalC2 software (Azapagic 2016) and 5,63 kg CO_2 eq (with SimaPro software (Pre-sustainability 2021)). According to this figure, the raw material acquisition stage was the main contributor to the CF in all software (92,83 % on average), with SimaPro software (Pre-sustainability 2021) contributing the least (81,64 %) and GEMIS software (Fritsche and Schmidt 2003) contributing the most (97,03 %). On the other hand, the manufacturing stage contributes on average 7,17 % considering all the software, with the GEMIS software (Fritsche and Schmidt 2003) contributing the least (2,97 %) and the SimaPro software (Pre-sustainability 2021) contributing the most (18,36 %). Indeed, as shown in Figure 1, OpenLCA (Ciroth 2007), GEMIS (Fritsche and Schmidt 2003) and CCaLC2 software (Azapagic 2016) report similar values (0,12 kg CO_2 eq, 0,11 kg CO_2 eq and 0,13 kg CO_2 eq, respectively). In contrast, the SimaPro software (Pre-sustainability 2021) reports a value of 1,03 kg CO_2 eq. manufacturing stage contributes to the CF in all software with only 7,17 % on average. The most significant contribution is in SimaPro software with 18,36 %.

Concerning the contribution of each process to the CF in the raw material acquisition stage, the process that most contributes to CF of wooden pallets is different between the software (see Figure 1). In OpenLCA (Ciroth 2007) steel production contributes 39,91 %, while in GEMIS (Fritsche and Schmidt 2003) and SimaPro (Pre-sustainability 2021) it is lumber production with 39,94 % and 39,18 % respectively. In CCaLC2 software (Azapagic 2016) the main contributor is lumber transportation with 65,77 %. These variations could be due to the different datasets available in the database of each software (see Table 3). For example, in the GEMIS software (Fritsche and Schmidt 2003), spruce production was considered, while in the OpenLCA software (Ciroth 2007) a mix of different types of softwoods (pine and spruce) was sustainably managed in Germany, Sweden, and Switzerland was considered.

Regarding the contribution of each process to the CF in the manufacturing stage (see Figure 1), the main contributor to the CF value of this stage, for all software, is the liquefied petroleum gas used in the forklift (91,11 % on average). A Slightly different result is obtained in OpenLCA software where this process contributes 82,32 % and in SimaPro where it contributes 97,73 %.

As indicated in the methodology, the inputs were obtained using the software's own databases (see Table 3). A few inputs were not found in those databases and were obtained from external sources. In the case of the OpenLCA software (Ciroth 2007) the entries for "liquefied petroleum gas" were obtained from EPA (EPA 2018) and the input for "diesel for electric generation" was obtained from the Agribalyse database (Wermielle and Colomb 2020) available in the same software. In the case of GEMIS (Fritsche and Schmidt 2003), the input for "liquefied petroleum gas" was obtained from EPA (EPA 2018) while "natural gas for electricity generation" was obtained from the BioGrace database (Neeft *et al.* 2015). In the CCaLC2 (Azapagic 2016) and SimaPro software (Pre-sustainability 2021), all inputs were obtained directly from the software databases. In the particular case of the Chilean electricity input, no such module was found in the open access software databases. Therefore, the module was built considering the Chilean energy matrix (Ministerio de Energía. Gobierno de Chile 2020). In the case of SimaPro software (Pre-sustainability 2021), the module was obtained directly from the Ecoinvent database. Additionally, the electricity module was also built in the SimaPro software (Pre-sustainability 2021) and the results were compared with the Ecoinvent module for the energy matrix of the Chilean electricity system, obtaining very similar results (a difference of 1,2 % between the two modeled electricity).

Carbon footprint of the plastic pallet

The CF results of the plastic pallet and the contribution of the inputs to each stage are shown in Figure 2. It is important to observe that the cooling stage is not presented since electricity is the unique input for this stage, and consequently no further analysis can be extracted from its contribution to this stage.

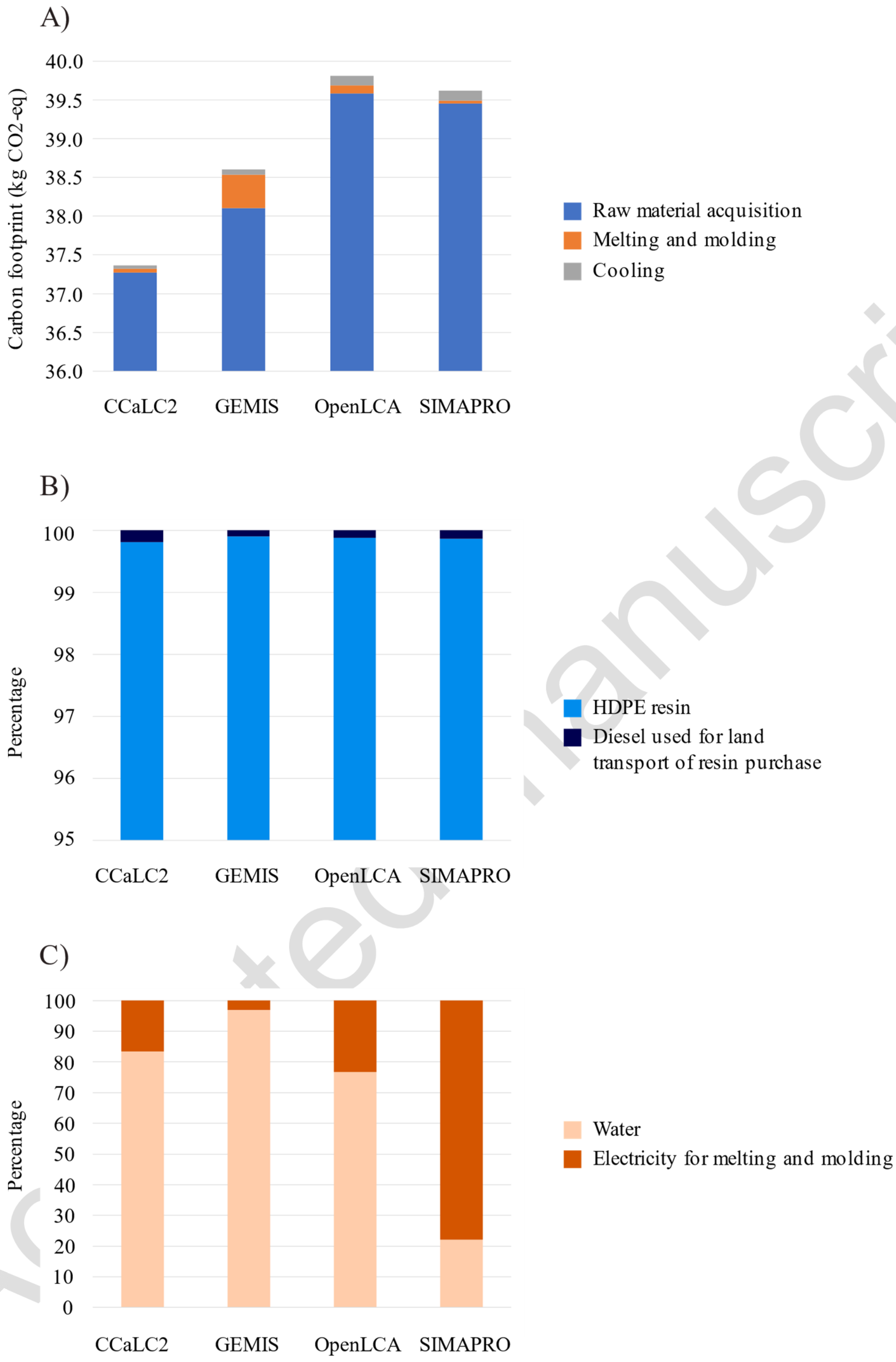

Figure 2: Total carbon footprint of the plastic pallet obtained by each software studied (A), and the percentage contribution of the process to raw material acquisition (B), melting, and molding stage (C).

Focusing on the total CF in each software, Figure 2 shows that the value of the CF ranges between 37,37 kg CO_2 eq (with CCalC2 software (Azapagic 2016)) and 39,81 kg CO_2 eq (with OpenLCA software (Ciroth 2007)). As with the plastic pallet, the raw material acquisition stage contributes largely to the total CF. In this case, the average contribution of the software is 99,36 %. In the GEMIS software (Fritsche and Schmidt 2003) this stage weights 98,71 %, while in the CCalC2 software it weights 99,75 %. On the other hand, the stages of melting, molding, and cooling contribute less than 1,12 % to the CF in all software, on average.

Concerning the inputs that most contribute to the CF in the manufacturing stage (Figure 2), the production of HDPE resin presents the highest impacts, weighting in all software 99,86 % of the CF of the raw material acquisition stage. The remainder 0,02 % contribution is due to the diesel used for transporting the resin until the plant. All software presents similar values for both entries.

Concerning the input contributions to the CF in the melting and molding stage (Figure 2), the production of HDPE resin presents the highest impacts. The input that contributes the most in the open access software is the use of water, while in the SimaPro software (Pre-sustainability 2021) it is the input of electricity. This could be due to the different datasets contained in the software. For example, focusing on the contribution of the different sources of electricity to the CF, in the case of CCaLC2 (Azapagic 2016) and OpenLCA (Ciroth 2007) it is electricity generation by coal (61,64 % and 63,20 %, respectively), while in the GEMIS software (Fritsche and Schmidt 2003) it is electricity generation by hydroelectric power (38,50 %). In the SimaPro software (Pre-sustainability 2021), since the electricity input has been used as a single module, there is no disaggregated result.

As in the case of the plastic pallet, some entries were not available in the software databases. In the case of the OpenLCA software (Ciroth 2007) the "diesel for electricity generation" input was obtained from the Agrybalyse database (Wermielle and Colomb 2020), available in the same OpenLCA software (Ciroth 2007). In the case of the GEMIS software (Fritsche and Schmidt 2003), the "natural gas for power generation" input was obtained from the BioGrace database (Neeft *et al.* 2015). In the CCaLC2 (Azapagic 2016) and SimaPro software (Pre-sustainability 2021), all entries were obtained from their internal databases.

According to the results presented in Figures 1 and 2, the wooden pallet presents lower CF compared to the plastic pallet. On average, the CF considering the database and the characterization factor used in each software, reported a ratio of 1:9 between wooden pallets (4,12 kg CO_2eq) and plastic pallets (38,85 kg CO_2eq). It is important to note that, in both types of pallets, the raw material acquisition stage is the one with the highest contribution to the total CF, showing the relevance of the raw material production processes for the CF of both pallets. Moreover, as previously mentioned, the biogenic carbon origin of the wood favors the CF value to be lower, however, this attribute is not present in the plastic due to the fossil origin of the carbon.

The results found are representative of this case study. This implies that the variations could be greater or lesser if other stages of the life cycle of the pallets are considered, other products are analyzed, or other environmental impact categories are evaluated, such as acidification, eutrophication, etc. For example, it is important to mention that future works could be modeled into the LCA the necessary inputs for wooden pallets that will be produced for export, inputs to thermal treatment, or the application of chemical compounds and so comply with sanitary regulations internationals.

On the other hand, it is also important to note that in the event of a change in FU, these results may vary. This is the case of the inclusion of use stage and consequent product lifetime, where the number of times a pallet can be used for transportation, known as cycles, is specified. A recent study by Khan *et al*. (2021) based on that reported by Deviatkin *et al*. (2019), indicates that wooden pallets could be used for 20 cycles, from a range of 5 to 30 cycles, while plastic pallets could be used for 66 cycles, from a range of 50 to 100 cycles. This wide range of pallet life is due to the handling and treatment of the pallets in operation and the load stacking conditions. This extension of more than 3 times the service life of the plastic pallet concerning the wood pallet could change the results of this study if use stage is included.

Comparison of results obtained with literature

Wooden pallets emit 8,2 kg CO_2eq per unit, according to a recent study developed in Costa Rica (Solano Salmerón *et al.* 2021). The same author, in a research conducted in 2018, points out that the wooden pallets production generated 6,87 kg CO_2eq with phytosanitary treatment and 10 kg CO_2eq with liquefied gas treatment. Carbon sequestered (biogenic CO_2 emissions) were accounted for in these calculations. Phytosanitary and liquified gas emit 2,86 kg CO_2eq and 3,07 kg CO_2eq, respectively (Solano-Salmerón *et al.* 2018). Therefore, our data are similar to this Latin American study. On the other hand, Deviatkin *et al.* (2019) reviewed the CF for wooden and plastic pallets from several countries (United States, Australia, Spain, Italy, Singapore, and the Czech Republic). From their results, it appears that the magnitudes of CF considering the cradle-to-gate system boundary are in the range of 3,1 kg CO_2eq to 20 kg CO_2eq. Comparing our results with those obtained by these researchers, it can be seen that the average CF magnitude in the wooden pallet is closer to the lower range. However, other studies of wooden pallets report emission values of 2,12 kg CO_2eq in Catalonia-Spain, whose system boundary comprised from the extraction of raw materials to the factory gate (García-Durañona *et al.* 2016) and 2,27 kg CO_2eq in an Italian company (Niero *et al.* 2014), which indicates that CF could be decreased with optimization strategies.

Regarding the plastic pallet, although some CF studies have been reported, they have been published with methodological aspects different from this study (Koci 2018, Anil *et al.* 2020). To the authors' knowledge, only Deviatkin *et al.* (2019) evaluated CF for plastic pallets using the same FU and the system boundary of our study. The magnitudes of CF reported by these researchers are in the range of 3,7 kg CO_2eq to 61 kg CO_2eq. Comparing our results with those obtained by these researchers, it can be seen that the average CF magnitude in the plastic pallet is closer to the upper range.

The use of different environmental impact assessment methodologies associated with each of the software could also induce a different CF value. This could be due to different characterization factors available in the methodologies. Table 4 presents the characterization factors of some substances emitted during the elaboration of wooden and plastic pallets. Taking as an example the methane, there is a difference of 29 % between the lowest factor (28 in CCaLC2 and SimaPro) and the highest factor (36,8 in OpenLCA). This is similar to other substances. This difference in the characterization factors can be due to the use of different methodologies. For example, the OpenLCA software (Ciroth 2007) uses the "Environmental Footprint" methodology in the PEF database, while the CCaCL2 software uses the CML methodology. This is more evident when several environmental impact categories are evaluated together. OpenLCA (Ciroth 2007) and SimaPro software (Pre-sustainability 2021), for example, allows the assessment of various impact categories. Additionally, CCalC2 (Azapagic 2016) and GEMIS software (Fritsche and Schmidt 2003) offer a predetermined impact assessment methodology, while OpenLCA (Ciroth 2007) and SimaPro software (Pre-sustainability 2021) allow environmental impacts to be assessed using different methodologies. Although these methodologies have the same method for obtaining the characterization factor (IPCC method), they may use different versions, e.g. IPCC (1996), IPCC (2006), or IPCC (2019).

Among the software evaluated, it was observed that some allow seamless integration of external databases, while in others the user must have more knowledge. For example, in the OpenLCA software (Ciroth 2007), the user can integrate databases directly, while the CCaLC2 software (Azapagic 2016) allows the integration of databases indirectly. This could mean a variation in the unit process used in the modeling of the products (as was the case for the wood pallet and plastic pallet) if the specialist does not take care to look for equivalent unit process available in the different databases, which requires some experience on the part of the modeler. However, even though all the software used in this study allowed the integration of external unit processes, this requires more knowledge of the software itself and therefore a higher level of expertise. Finally, it is important to note that the development of a national database would contribute to the reduction of variability by considering aspects specific to local/regional production systems, as previously indicated in some publications (Perić *et al.* 2020, Ramos-Huarachi *et al.* 2020).

The above reflections are consistent with what has been published by some authors (Ormazabal *et al.* 2014, Lopes Silva *et al.* 2019, Pauer *et al.* 2020) who point out that the use of software (databases and methodologies) for LCA modeling could generate different results in the determination of environmental impacts, with what was found for carbon footprints in the present research.

Table 4: Environmental characterization factors of some substances emitted during pallet elaboration[a].

Substance	Formula	OpenLCA (PEF database)	CCaLC2 (CML and own database)	GEMIS (Own database)	SimaPro (CML database)
Methane	CH_4	36,8	28	30	28
Nitrous oxide	N_2O	298	298	265	265
Trifluoromethane	HFC-23	13900	14800	12400	12400

[a] All values are in kg $CO_{2\text{-eq}}$ / kg substance

CONCLUSIONS

When comparing the CF in local use pallets made of wood and plastic, it can be concluded that wood presented a better environmental performance, since the calculated CF values showed a magnitude 9 times lower in the wooden pallet than in the plastic pallet. In the production process of both pallets, the stage that generates the greatest contribution to this environmental impact is the acquisition of raw materials (steel, wood, and transportation in wooden pallets and resin in plastic pallets). However, it is important to note that this conclusion may vary if a different FU is considered, such as one that considers the use of the product, among other aspects.

The use of different software tools for the calculation of CF has shown a greater variability in the measurement of the wooden pallet than the plastic pallet. The reason for this variation is mainly due to the selection of international or global databases and as a solution, it is proposed the generation of national or local databases to be used in the software, which allows a better representation of reality.

Based on the results obtained and the variations observed, some advantages and disadvantages can be observed in the use of this methodology for the quantification of the CF of the product. Among the advantages, it can be pointed out that the gathering of information through inventories, considering the unitary processes that cover the scope of the study, allows a very detailed knowledge of the stages, raw materials, and energies that are necessary for the manufacture of the pallets with their different materiality. This systematization of the information allows identifying quantities and the origins that are necessary to know if the industry plans to optimize its process. Once the data are simulated with the help of the different software, one of the main advantages is to have the information of potential impacts that can be produced by the product being manufactured and to define the critical processes and causes that originate them. However, the disadvantages, such as variation of the results depending on the databases that the software uses for its modeling, allow proposing the use of this tool for decision making, by professionals who know very well the processes and their equivalence with the unit process offered by the databases with which the software is linked, thus avoiding errors in quantification and future decisions by the producer.

In addition, future studies intend to address further analysis regarding the use of open access software for the publication of findings in scientific journals. This will be discussed in a forthcoming publication (in preparation). On the other hand, it is suggested to analyze the source and reuse of raw materials and logistics (location and mode of transport) and to analyze the quantification of the CF of pallets destined to the foreign market, together with the measurement of other impact categories that allow providing information for more environmentally friendly and holistic decision making, bearing in mind that Chile is a country that generates foreign currency through export activity, where pallets become a strategic element in the transportation of raw materials and products.

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