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Beyond ecodesign, internationalized markets enhance the global warming potential in the wood furniture sector

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ABSTRACT

Circular Economy principles encourage the implementation of bio-based and renewable materials over non-renewable technical counterparts. Wood-based materials can effectively address finite resource depletion and the accumulation of non-biodegradable waste into terrestrial and marine environments. In this context, the furniture industry has long relied on the use of wood for manufacture goods. However, the use of renewable materials is not directly translated into sustainable consumer goods. Accordingly, this work analyzes the life cycle environmental impacts of an eco-designed and locally-manufactured wooden bunk bed and compares local and international market scenarios to understand its *cradle-to-grave* environmental footprint. Using primary data, the life cycle assessment (LCA) methodology is followed to quantify and compare the environmental impacts of a currently commercially available wooden bunk bed over alternative scenarios. To facilitate future comparison, 1 kg of furniture is used as a functional unit. The *cradle-to-grave* system boundaries are established according to the reference *"Furniture, except seats and mattresses"* Product Category Rule. The *upstream*, *core* and *downstream* life-cycle stages are considered, and the environmental impacts are presented into eight different categories. To provide the bigger picture, obtained results are compared with literature. A *cradle-to-grave* CO_2-eq footprint of 1.71 kg per kg of an already eco-designed bunk bed is obtained, 15.1% below average traditional furniture. The *downstream* stage contributes to the 58.3% of the total greenhouse gas emissions, while the *upstream* and *core* phases present a share of 26.2% and 15.5%, respectively. Such a large contribution of the downstream phase originates from the transportation to the final customer (82.6% of this phase). For *upstream* and *core* phases, plywood production (53.1% share during the *upstream*) and electricity consumption (75.1% share during the *core*) are the main hotspots. Furthermore, this work quantifies the global warming potential of current internationalized wood furniture markets. Local furniture sale can reduce the CO_2 emissions of the wooden bunk bed by 40%. Instead, selling the bed abroad involves a CO_2 emission increase of 59%, while raw material importation enhances the impacts by 39–45%. The adoption of local production and consumption patterns emerge the most effective measures to reduce the environmental impacts of the furniture industry as the purchase of an overseas manufactured wood bunk increases the emissions by 79%. This research aims not only to bring light in the scientific community in LCA calculations but also help producers and consumers in the transition towards more sustainable consumption and production patterns in the wooden furniture market.

1. Introduction

The last Intergovernmental Panel on Climate Change (IPCC) report on climate change has shown that greenhouse gas emissions are rising and that the current plans aimed to address climate change are not ambitious enough to limit global warming to 1.5 °C above pre-industrial levels. The associated climate crisis may cause severe alterations in our environment, with more abundant extreme temperatures, droughts,

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heavy rainfall, floods, rising sea levels, loss of biodiversity, or seawater acidification (Intergovernmental Panel of Climate Change, 2014). On this basis, our society urgently needs to transition towards environmentally sustainable and responsible production processes. The widespread implementation of bio-based and renewable materials over non-renewable technical counterparts such as plastics or metals results an effective approach to address finite resource depletion and the accumulation of non-biodegradable waste into terrestrial and marine environments. In this line, policymakers are also calling to expand the use of regenerative and bio-based materials, which adheres to the Circular Economy principles (Ellen MacArthur Foundation, 2017). Furthermore, the "IPCC AR6: Mitigation of Climate Change" report has already shown (Intergovernmental Panel of Climate Change, 2022), following the research performed by Akizu-Gardoki et al., the feasibility to reduce the energy-related environmental impacts while increasing the Human Development Index (HDI) thought a consumption-based accountability of energy reduction, the so-called decoupling (Akizu-Gardoki et al., 2018). However, to effectively decouple maintaining high life standards with lower consumption levels, the embodied product energy and associated impacts during the complete life cycle should be measured. This avoids a virtual decoupling scenario with hidden environmental affections upon manufacturing externalization overseas, which reduces national impacts at expenses of increasing total average global impacts.

In this regard, the furniture and furnishing sector is one of the sectors traditionally had a one of the greatest share of renewable raw materials, mostly from wood origin. Durable furniture is present in many areas of our life as they can be found in homes, restaurants, retail sectors and workplaces (Renda et al., 2015). The European furniture industry accounts for an approximate market of 84 billion euro and employs one million people (European Environmental Bureau, 2017). Although conventional manufacturing of furniture uses a wide range of materials such as wood, metal, plastic, textile, leather and glass, nearly the 60% of the furniture fabricated in the European Union is bio-based, either in the form of solid timber wood or plywood (Renda et al., 2015). In addition, wooden furniture present an added value compared to furniture made of other materials because, given its organic origin, wood contains stored CO_2 (Iordan et al., 2018). In fact, the substitution of non-wooden good by wood-based ones significantly contributes to impact reductions such as climate change, resource consumption, and urban air pollution. However, to avoid the transfer of environmental impacts, minimizing land transformations from forest to barren land by replanting after clear-cutting or by conducting selective cutting will be required (Kayo et al., 2019). Generally, plywood is mostly used over solid timber because it is cheaper and easier to assemble. When compared with timber, plywood could present added environmental burdens due to the presence of formaldehyde-based resin adhesives (Salem et al., 2012). A recent study reveals that plywood has larger embodied carbon dioxide emissions over solid wood, although ~2-to-3 times lower than plastics and polyurethane (Asdrubali et al., 2017). In fact, recent environmental impact assessment studies reveal that climate-change impacts could be 90% lower when plywood replaces other types of materials (substitution) (Suter et al., 2017). However, it should be bear in mind that although wood-derived products are commonly classified as environmentally sustainable, their actual sustainability depends on aspects related to appropriate forest management, manufacturing methods, site assembly, the distance required for transportation (large impacts associated to the transport of bulky goods), the use of adhesives (Asdrubali et al., 2017). Accordingly, the current wood-based furniture industry has significant room for improvement towards friendlier approaches.

The transition to circular and sustainable production models needs unambiguous quantification of the environmental impacts to establish whether the strategies adopted contribute to more efficient production systems. In this light, several works addressing the environmental impacts of plywood production have been published so far (dos Santos et al., 2014; Garcia and Freire, 2014; González-García et al., 2009; Silva et al., 2013). However, to the best of our knowledge, no scientific manuscripts have been publishing quantifying the impacts associated with the production of furniture based on solid wood timber. In addition, the comparison on how delocalized and local manufacturing in the furniture industry affect the environmental impacts remain unclear. Accordingly, there is a need for further analyses on the environmental impacts of furniture in a comparative and well-established methods (Cordella and Hidalgo, 2016). Providing transparent, reliable and comparable data accounting for the environmental impact of furniture can help manufacturers to achieve sustainable production processes while assist consumers to make sustainable and well-informed choices (Levesque et al., 2022).

The environmental impacts could be quantified *via* life cycle assessment (LCA) methodology, which is often used to account for the impacts of a material, process, product or a service through the (entire or partial) life cycle (Kousemaker et al., 2021; Sillero et al., 2021). Unfortunately, achieving accurate, reproducible and comparable impact assessment is one of the well-recognized shortcomings of LCA (Thonemann et al., 2020). To solve these issues, several standardized procedures have been developed over the last years. Nowadays, the Environmental Product Declaration (EPD) is considered as a powerful tool to obtain relevant and comparable information on the environmental performance of products or services (Del Borghi, 2013). As opposed to certain certificates such as "FSC Certification" that require minimum standards, EPDs do not consider minimum environmental requisites. On the contrary, the aim of EPDs is to communicate verifiable, accurate and non-misleading environmental information, facilitating comparison between products and applications with related characteristics. In doing so, the impact assessment should be performed according to specific Product Category Rules (PCR), which are disclosed in ISO 14025, ISO 21930 and EN 15804 standards. These PCRs define the rules for a specific group/category of products/services so the EPD could provide contrasted information on the environmental functionality (Del Borghi et al., 2020; Ingwersen and Stevenson, 2012).

The aim of this study is twofold. Firstly, to assess the *cradle-to-grave* environmental impacts of a bunk bed under current scenario so possible impact hotspots are identified, facilitating further optimization through eco-design (Kamalakkannan and Kulatunga, 2021; Polverini, 2021). The results are grouped into *upstream*, *core* and *downstream* lifecycle stages according to the *"Furniture, except seats and mattresses"* PCR Version 2.01 (published in 2019 and valid until 2023-06-17) in the point "4.4 System Diagram", that follows EN 15804/ISO 21930 (EPD International AB, 2019). Secondly, four alternative scenarios are analyzed so the role of local manufacturing and selling on the overall impacts could be understood. To do so, global market variables into a commercially available eco-designed wooden bunk are implemented. Paired with primary data and PCRs, the knowledge here gathered aims to open new possibilities for strategic decisions and enable the implementation of sustainable production patterns in the wooden furniture industry/market.

2. Methods

2.1. LCA goal and scope

This work uses the LCA methodology to quantify and compare the environmental impacts of a bunk bed. The study is based on primary data after a collection and analysis of the inputs and outputs of the system from the manufacturer (Muebles LUFE). LCA has been carried out based on the ISO 14040:2006 and ISO 14044:2006 standards. Accordingly, after defining the objective and scope, the life cycle inventory (LCI) is established, the life cycle impact assessment (LCIA) is performed and finally, the interpretation of the results is done (Alejandre et al., 2022). LCA is performed following the *"Furniture, except seats and mattresses"* Product Category Rule. In addition, local and international market strategies are applied on top of the eco-designed furniture to study novel scenarios with potential reductions on the environmental

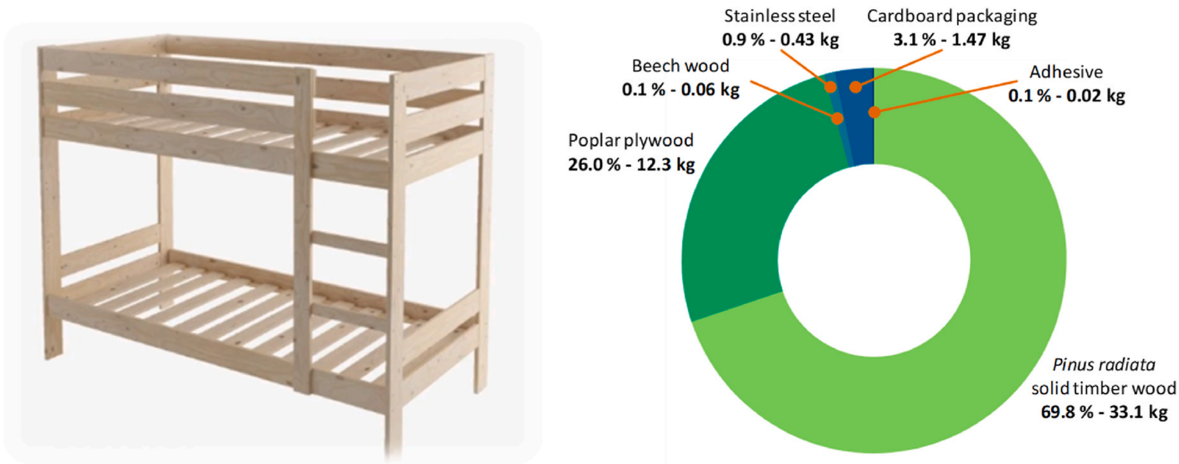

Fig. 1. Physical appearance and composition of the LORE 90 bunk bed manufactured by Muebles LUFE.

impacts (Civancik-Uslu et al., 2019).

This work quantifies and analyzes the environmental performance of the "LORE 90" bunk bed produced by Muebles LUFE (see Fig. 1), comparing obtained results with related furniture, and optimizing its environmental performance using alternative market strategies. Muebles LUFE is located in Aizarnazabal, Gipuzkoa (northern Spain). The double bunk bed uses wood originating from *Pinus radiata*, which is certified by the Programme for the Endorsement of Forest Certification (PEFC) certificate. The product has been already eco-designed using the lowest quantity of raw material during production, upon the reduction of the constructions items, limiting manufacturing processes, selling disassembled furniture to facilitate an efficient packaging and using wood from local resources. In fact, the wood originates from a sawmill located 70 km from the manufacturer (55 km between the mill and the origin of the wood). The bed is 99 cm wide, 190 cm long and 160 cm high, and could withstand up to 200 kg of load. The composition of the bunk bed is given in Fig. 1 and Fig. S1. The sale process is online, directly between the company and the end-user, so no intermediaries are found. The determination of the functional unit (the product, service, or system to which the impacts are normalized, FU) should follow the reference PRC guidelines, which establishes the FU as a product unit, including its packaging and maintenance during the complete lifetime. The lifetime is defined as the time-span at which the bed keeps its function, considering both technical and aesthetic aspects. In the absence of historical and statistical data on the useful and effective life of the furniture, the PCR enables to consider a default lifespan of 15 years (EPD International AB, 2019). The PCR "Furniture, except seats and mattresses" (UN CPC 3812/3813/3814) allows to define the LCA boundaries, system diagram

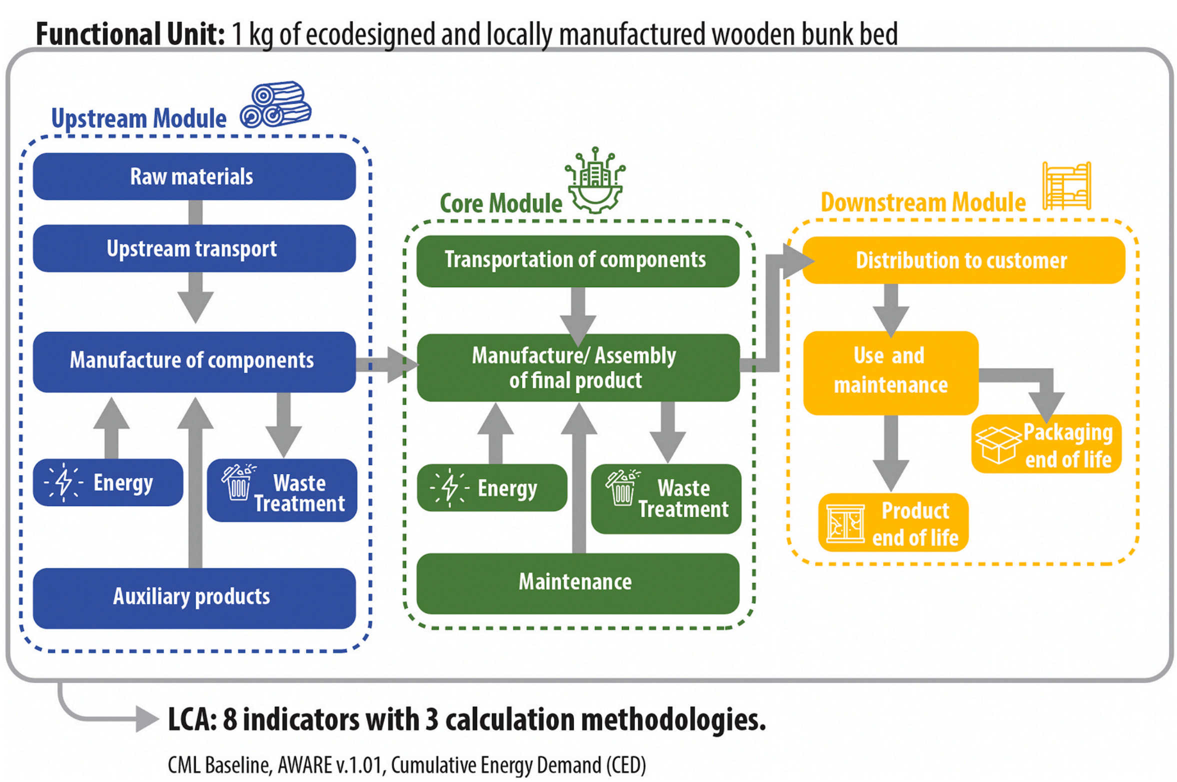

Fig. 2. LCA scope and boundaries for the studied bunk bed based on the "*Furniture, except seats and mattresses*" PCR. The use of raw materials is accounted from the "manufacture of components" phase.

and disaggregation level, allocation rules, cut-off rules, data quality requirements and the required impact categories to make valid the comparison (EPD International AB, 2019). Accordingly, the FU for the "LORE 90" bunk bed is the complete bed including its packaging (47.4 kg) for a period of 15 years. However, this FU does not enable the comparison of obtained impacts with related furniture. Therefore, to facilitate comparison with other studies on the environmental impacts of wooden furniture; 1 kg of fabricated bunk bed is set as the FU. The system boundaries are established according to the reference PCR, where attribution processes from *cradle-to-grave* perspective are included following the "limited loss of information in the final product" principle (de Lapuente Díaz de Otazu et al., 2021). Accordingly, the life cycle is divided into the following three stages: *upstream*, *core* and *downstream*. Fig. 2 is drawn to facilitate the understanding of the objective and scope of the work, which has a *cradle-to-grave* perspective according to the reference PCR. As established by the followed PCR (UN CPC 3812/3813/3814), the manufacture of production equipment, buildings and other capital goods, business travel of personnel, commuting to work, and research & development activities are not considered.

The *upstream* stage considers:

○The extraction and manufacturing of raw materials, including solid timber pine wood, plywood and stainless-steel hardware. The dataset covers the production and harvesting of 1 m^3 of stem-wood, together with the relative share of energy wood from forest management.
○The extraction and manufacturing of the final product packaging based on cardboard.
○The energy consumption.
○The associated transport from extraction to production of the raw materials.
○The generated waste during the production of the raw materials.

The *core* stage considers:

○The transportation of raw materials and packaging to the factory.
○The energy associated with the fabrication/manufacturing of the bunk bed.
○The generated waste during the production of the bunk bed parts.
○The maintenance of the industrial machines required for manufacturing.

The *downstream* stage considers:

○The transportation to the end-users estimated on the base of Muebles LUFE sales: 450 km from the factory to Madrid, Spain.
○The maintenance and use of the product during 15 years (although the product does not require maintenance as such, the wood may be damaged and certain parts are considered to be replaced (according to the primary information provided by the manufacturer). These parts include the two front bars, and the two steps of the staircase. A varnish coating is also considered.
○The end-of-life (EoL) scenarios for the product and packaging materials.

LCA has been carried out using the OpenLCA 1.10.3 software and Ecoinvent 3.8 database (Wernet et al., 2016). There are works claiming that wood can be modeled with an atmospheric carbon storage of 2.09 kg CO_2-eq per 1 kg of furniture (Iritani et al., 2015). As a result, final negative impacts could be obtained for wooden furniture in the global warming potential (GWP) impact category (−0.96 kg CO_2-eq per 1 kg). However, we do not consider the sequestered carbon for the calculations because we assume that the stored CO_2 will be released to the atmosphere at the end-of-life of the furniture, which will be certainly shorted than 100 years. This method has been also followed by González-García to account for the impacts in the wood sector (González-García et al., 2012). According to the PCR, the impact categories that should be analyzed are: GWP, acidification potential (AP), eutrophication potential (EP), photochemical ozone creation potential (POCP), abiotic depletion potential – elements (ADPe), abiotic depletion potential – fossil fuels (ADPff), water scarcity potential (WSP) and the energy footprint (EF) divided into 6 sub-categories. The EF accounts for the energy use per kg of material processed. More precisely, it measures the direct and indirect energy use throughout the life cycle, including the energy consumed during the extraction, manufacturing, and disposal of the raw and auxiliary materials (Huijbregts et al., 2006). As it is possible to distinguish between energy requirements of renewable and nonrenewable resources, the EF in this work is divided into: non-renewable (fossil), non-renewable (biomass), non-renewable (nuclear), renewable (biomass), renewable (water) and renewable (wind, solar, geothermal). Accounting for EF is particularly useful when analyzing energy-intensive product systems and it gives easily understandable value (Wiesen and Wirges, 2017). GWP, AP, EP, POCP, ADPe and ADPff are calculated based on CML-IA baseline; AWARE (Available WAter REmaining) method is applied to obtain the WSP and cumulative energy demand (CED) methodologies were used to quantify the EF (Huijbregts et al., 2010). CED has been applied to account for the energy footprint because it represents the closest available method to the one defined by the reference PCR.

2.2. Life cycle inventory

Overall, the PRC document contains instructions to perform the life cycle assessment of a series of products fulfilling different needs. Further details not covered by the ISO 14040 and ISO 14044 standards are provided to ensure uniform and comparable results for functionally similar products. In doing so, the FU, the system boundaries, the impact categories to be studied and the accepted cut-off criteria are defined. To adhere to the "*Furniture, except seats and mattresses*" PCR, data on elemental flows to and from the product system contributing by at least the 99% of the environmental impacts are covered. The life cycle inventory of *upstream, core and downstream* life-cycle stages is provided in the Supporting Information as Tables S1–S3. All the data correspond to the year 2021, and the information used is obtained as:

- Primary data directly provided by Muebles LUFE for the 100% of the bunk bed, including the data regarding the environmental aspects of the system, raw materials, packaging, energy consumption, the generated waste, transport distance, manufacturing equipment maintenance, bunk bed use, emissions and discharges. As so, the life cycle inventory is fully and unambiguously defined, solving one of the major bottlenecks faced during the LCA carried out by universities or environmental agencies.
- Secondary data originating from the Ecoinvent 3.8 database related to the production processes of raw materials and packaging, the waste generated and energy consumption in these processes and the associated transport from extraction to production of the components. The EoL scenarios proposed for the product and packaging are also secondary data. This database was released on 2021 and it is one of the newest and updated information sources, with new and updated datasets for the wood and metal sectors.
- To increase data reliability, the different electric mixes from Spain, the Autonomous Community of the Basque Country and the one of the LUFE factory itself have been modeled. Furthermore, the secondary data for sawn wood beams has been adjusted to simulate primary data by including own generated energy data for each specific region.

It is important to note that data availability is considered by the wooden furniture field as one of the main bottlenecks to accurate impact assessments (Linkosalmi et al., 2016; Iritani et al., 2015). Actually, the majority of the studies undertaken to date regarding the environmental

Fig. 3. Summary of the proposed alternative scenarios.

sustainability of the wood furniture industry rely on secondary data to determine the inventory (Linkosalmi et al., 2016; Mirabella et al., 2014; Piekarski et al., 2017; Iritani et al., 2015; González-García et al., 2009, 2011; Bovea and Vidal, 2004). In addition, *cradle-to-gate* impacts not adhering to the specific PCR are assessed by these works. Thus, this present work represents an additional effort to obtain accurate impact values by using (mostly) primary data, analyzing the complete life cycle and following the corresponding PCR. Our model is constructed for the year 2021, which is considered as the last representative year of a normal activity. The information in the LCI considering energy and raw material consumption is real and traceable, as well as those related to production, waste management, waste and emissions in use of the product. The data regarding material transport from the suppliers to Muebles LUFE relates to the average supplier distance.

2.3. *Sensitivity analysis*

To guide practitioners and industry towards cleaner production patterns, new scenarios (summarized in Fig. 3) are considered and their environmental impact is evaluated as follows (the corresponding life cycle inventories for the new scenarios are disclosed in Tables S4–S24):

- *Scenario 0*: it represents the base scenario, where the wood originates from *Pinus radiata* under PEFC certification and travels 70 km from its source to the factory. A distance of 450 km exists between the manufacturer and the sales-site (Aizarnazabal to Madrid). The bunk bed is maintained for 15 years, and EoL for the product and packaging materials are considered.
- *Scenario 1*: furniture is sold on the domestic market. Firstly, an average distance of 80 km is estimated from the manufacturer to the customer so the bunk bed is sold within the Autonomous Community

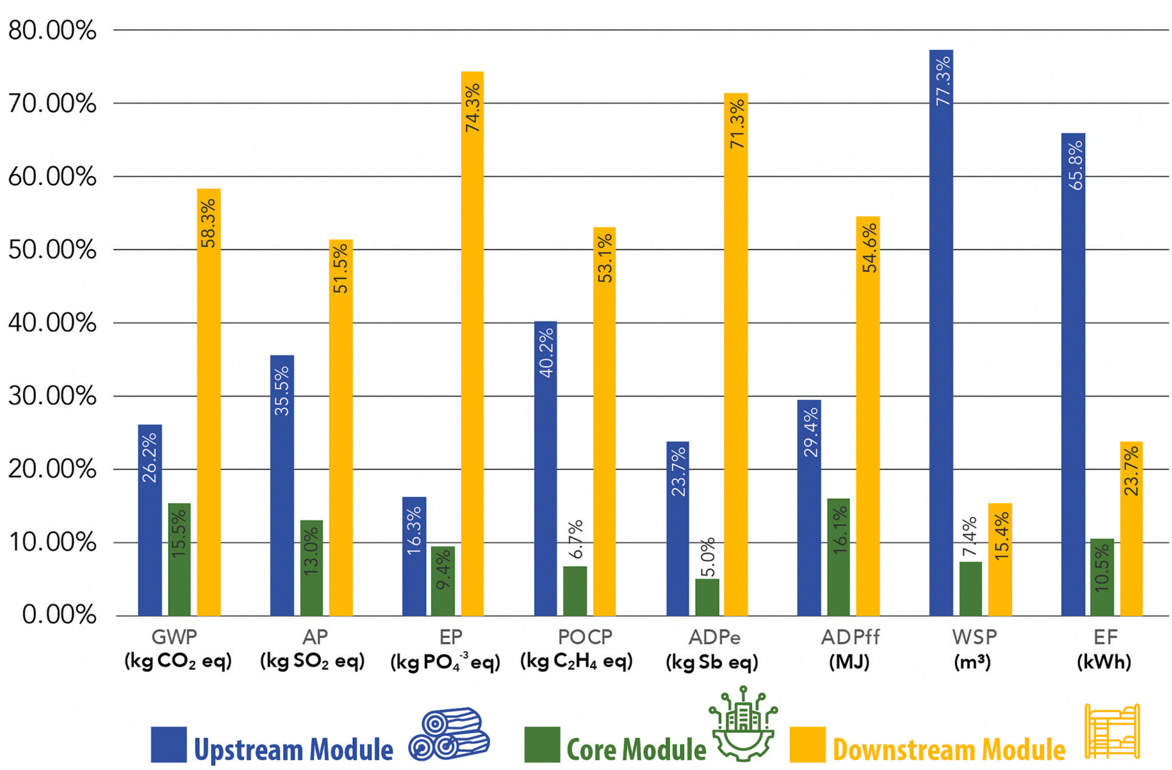

Fig. 4. Environmental impacts of the LORE 90 bunk bed (FU: 1 kg) for the *upstream*, *core* and *downstream* stages. Absolute data is provided in the Supporting Information, Table S25.

of the Basque Country (northern Spain). In addition, an additional situation with an average distance of 1000 km is also estimated so the bunk bed is sold in the southernmost extreme of Spain (Andalusia) or neighboring countries such as France or Portugal.

- ➢ *Scenario 2*: solid timber and plywood are imported rather than locally sourced. Three cases are assumed. 2.1: the wood originates from another autonomous community (600 km). 2.2: the wood originates from Germany (1650 km); 2.3: the wood originates from China (50 km to the train station, 12,600 km by train and 46 km by road to the factory, a total of 12,696 km). Germany and China are selected given their role as major wood exporters.
- ➢ *Scenario 3*: keeping manufacturing conditions unchanged, the goods travel from the city of Yiwu (China) to Muebles LUFE by rail transport (12,600 km). This is based on the actually operating Yiwu-Madrid line. After manufacturing, the bed is transported to Madrid (450 km) to be sold, similarly to the *Base Scenario (or Scenario 0).*
- ➢ *Scenario 4*: the use of photovoltaic solar energy is considered. The Spanish energy mix used is modified to model the actually manufacturing conditions at Muebles LUFE so the energy source is fully renewable.

3. Results and discussion

3.1. Environmental impacts of the bunk bed

Firstly, we quantified the *cradle-to-grave* environmental impacts of the LORE 90 double-bunk bed according to the "*"Furniture, except seats and mattresses*" PCR. The assessment covers the 100% of the weight of the furniture and uses primary data, which enables compliance with the PCR that requires the inclusion of >99 wt% of the components. The impacts in Fig. 4 are disclosed for the *upstream*, *core* and *downstream* lifecycle stages (Table S25 reports the absolute data). An equivalent *cradle-to-grave* CO_2 footprint of 1.71 kg CO_2-eq per kg of bed is obtained, where the plywood production and the transportation of the furniture to the end-user are the main contributors. This value is of similar order of magnitude than the 0.43 kg CO_2-eq per kg of wine crate (González-García et al., 2011a), the 4.84 kg CO_2-eq per kg of office table (González-García et al., 2011b), or the 7.27 kg CO_2-eq per kg of wardrobe produced in Brazil (Iritani et al., 2015). In particular, with an average value of 58.3%, the *downstream* phase is the stage having the largest environmental burden in all of the analyzed categories (see Fig. 4 and Table S25) excluding the water scarcity (15.4% share) and the energy footprint (23.7% share) categories. On the contrary, the *core* phase is the stage with the lowest overall footprint throughout the life cycle for all the categories (average contribution of 10.4%). This result matches the conclusions drawn by Iratani et al., who observed a predominant share of raw material supply and product distribution phases to the overall impacts (Iritani et al., 2015). The energy footprint distribution shows the direct and indirect energy use throughout the life cycle (Huijbregts et al., 2006). Interestingly, a partial contribution of biomass-based renewable energy is used during the lifecycle of the national energy system (1.1%) and in the Autonomous Community of the Basque Country regional energy system (3.2%); including biogas and solid urban waste (Table S26). This energy consumption profile is advantageous over fabrication technologies largely based on non-renewable energies as it reduces our dependence on fossil- or nuclear-based energy. This result encourages the implementation of sustainable integrated bio-refineries able to convert of biomass (wood) waste into bio-energy and fine-chemicals (Yuhe et al., 2020).

The *upstream* phase is a notable source of impacts (see Tables S25 and S27). The plywood production contributes markedly to the overall impacts (53.1%), followed by the sawn wood production (Fig. S2). This result originating from the notable contribution of wood preparation to the overall impacts (González-García et al., 2009), markedly contrasts

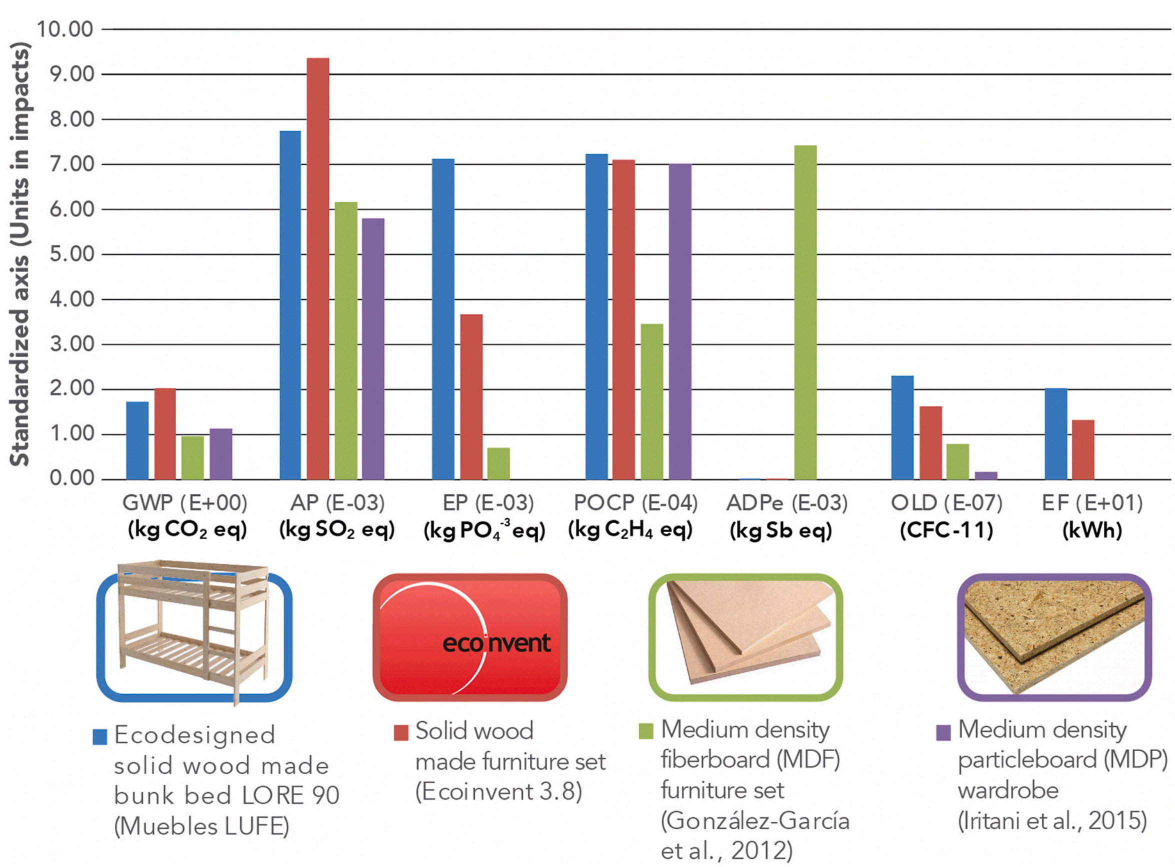

Fig. 5. Comparison of the environmental impacts of studied bunk bed with published results on wooden furniture (FU: 1 kg of furniture).

with the bunk bed composition, where 70% of the weight originates from solid timber wood and 26% from plywood. To explain the high impacts originating from the plywood, its production and composition should be analyzed. Plywood is composed by veneers or thin wood layers/plies (each layer is arranged perpendicular to one another) which are bonded by an adhesive. Its manufacturing process involves debarking (removing bark from wood), peeling, drying, sorting, gluing, laying up, and final hot pressing (Jia et al., 2019). Its peculiar structure results in superior advantages in terms of workability, shock resistance, durability, resistance to extreme weather conditions and moisture, and natural appearance over other wood-based composite materials (Ashori et al., 2018). However, its production encompasses non-environmentally sustainable processes (How Products are Made). Specifically, plywood it's made using sawed wood into desired sizes that after drying are then glued together by formaldehyde adhesives which bond the thin veneers of wood. Firstly, particulate matter consisting of wood dust is released into the air during wood cutting, bark removal, plywood sanding and plywood cutting. Small wood pieces are heated and soaked into a warm water solution to slice the wood, which is then dried to emit air pollutants in the form of organic compounds such as methanol (the energy consumption should be also here considered). Finally, the veneers are glued and hot pressed using adhesives to form plywood, when several air pollutants may be emitted. While phenol-formaldehyde adhesives are used for the exterior side due to their good moisture resistance, urea-formaldehyde glues are usually found in the interior of the plywood. In this sense, manufacturers control the emissions using methods such as absorption/oxidation systems, wet electrostatic precipitators and electrified filter beds. Besides of the multi-step production process, the EoL of plywood can be problematic as these chemical adhesive hardly decompose under landfill conditions and can even result toxic to the environment when exposed to extreme heat (conventional chemical adhesives are abundant in volatile organic compounds, VOCs) (Asim et al., 2018). In addition, conventional plywood may undergo through diverse chemical treatments to extent its lifespan, increasing the amount of materials that cannot be recycled. As a result, the fabrication of furniture using solid timber wood seems to be an environmentally preferred option over the use of plywood. In this context, the replacement of petrochemical adhesives by bio-based and fossil-free adhesives (soy-based (Lei et al., 2014) or those based on lignocellulosic biomass including Kraft lignin, Organosolv or tannins (Siahkamari et al., 2022)) has been highlighted by Moreira et al. as a plausible approach to lower the environmental impacts of wood furniture made by plywood. This shift from fossil-based to bio-based avoids formaldehyde emissions to air and water, greenhouse gas emissions, methanol/phenol emissions and additional volatile organic compound emissions(Arias et al., 2021; González-García et al., 2011a,b).

Regarding the *core* stage (see Supporting Information, Table S28), the energy consumption has the largest burden for 6 of the 7 analyzed categories. Wood transportation has a notable share (32.3%) for the abiotic depletion potential-elements, while with a 68.4%, the wood-waste treatment is the bigger contributor to the eutrophication potential category. A more detailed look at the *downstream* stage could shed more light on the notable environmental impacts of this phase (see Supporting Information, Table S29). The transportation to the final user results the process that contributes most in 6 of the 7 categories, which may originate from the extensive fossil fuel consumption. These results agree well with literature on wood-products, where transportation is identified as the largest contributor (dos Santos et al., 2014; Murphy et al., 2015). In fact, the improvement of the transportation system is regarded as the most effective yet realizable strategy to lessen the

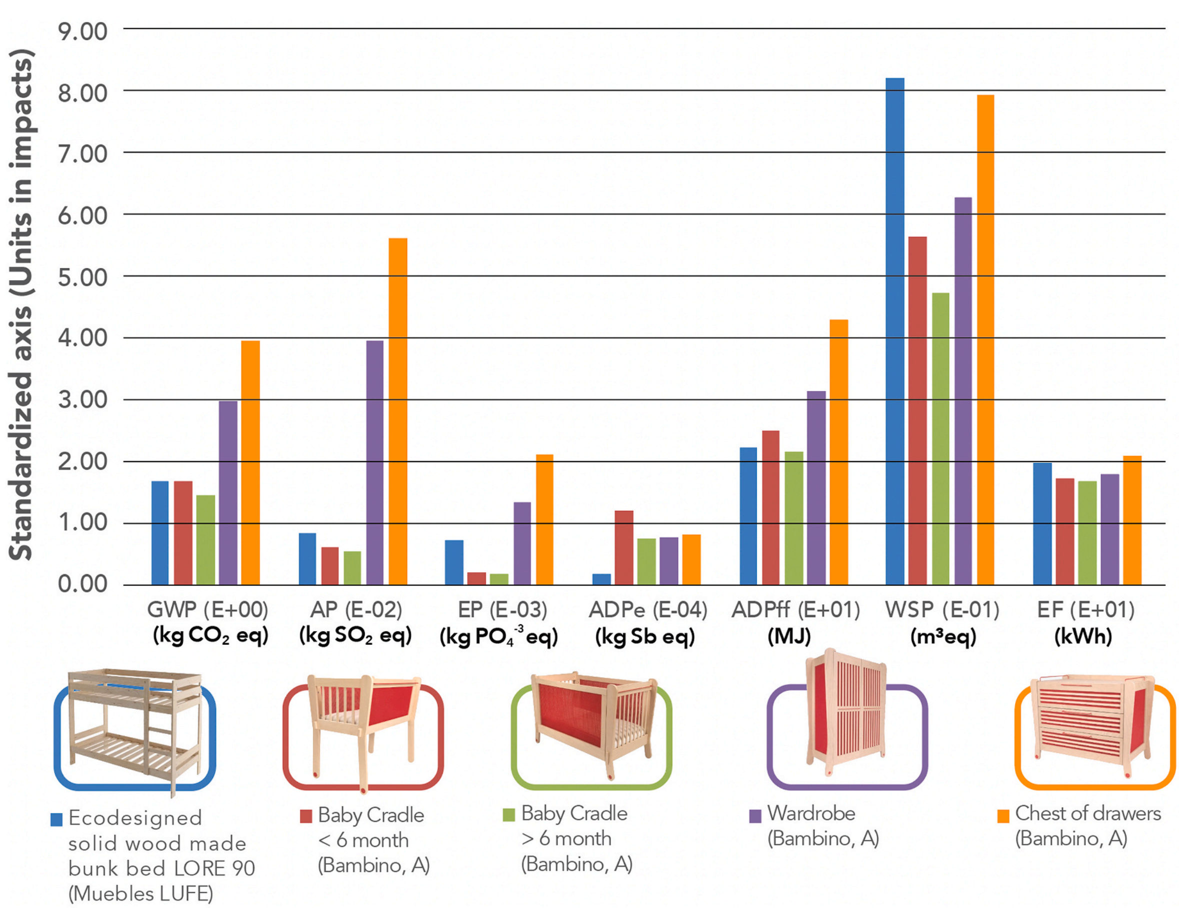

Fig. 6. Comparison of the environmental impacts of studied bunk bed with LCA studies performed following the *"Furniture, except seats and mattresses"* Product Category Rule.

environmental footprint of wood-based goods (Medeiros et al., 2017). When the distances between the wood source and the manufacturer are small, Linkosalmi et al. found that the material and energy supplier selection play a determinant role to lower greenhouse gas emissions (Linkosalmi et al., 2016). As will be discussed in the next section, these results encourage the implementation of bio-refinery strategies and wood cascading concepts. In particular, the cascading-use of wood furniture enhances material efficiency and boosts circularity as the materials are kept within the loop for longer (Russell et al., 2022). In addition, local sourcing and selling could be pursued to design environmentally-friendlier furniture and smoothly transition towards sustainable production practices.

3.2. Comparison with other furniture

To put these results in a broader context, the impacts are compared with the literature. Although several studies report the *cradle-to-grave* CO_2 footprint of wood furniture (González-García et al., 2011; Iritani et al., 2015), the comparison of obtained data is complex. In this sense, three representative examples have been selected for comparison as they report the environmental impacts not only in CO_2 emissions but also in additional impact categories considered by the EPD here followed. However, it should be noted that these works do not specifically adhere to the EPD, so the procedures to impact assessment may change. Fig. 5 compares the environmental impacts with previously reported wooden-furniture. The LORE 90 furniture shows a 15.1% lower GWP and a 9.8% lower AP in comparison with the traditional wood furniture modeled by Ecoinvent 3.8 database. Nevertheless, the GWP reported for a set of furniture comprising a baby cot, a study desk and a bedside table, are 44.3% below those obtained for the eco-designed bunk bed (González-García et al., 2012). The lower impacts may originate from the applied *cradle-to-gate* boundary that neglects the use and end-of-life impacts. In addition, the modeling parameters not disclosed by the corresponding PCR are used in the work by González-García et al., which in combination with the different material used. Besides, different materials were used for the furniture as González-García et al. analyzed furniture composed by medium density fiberboard, a composite material consisting of cellulosic fibers in combination with a resin and joined upon heat and pressure. Similarly, Iritani et al. studied the impacts of a wooden wardrobe produced in Brazil using medium density particleboard, resulting in 33.8% lower impacts in the GWP category (Iritani et al., 2015). These results are explained by the fact that the medium density particleboard is a pressed wood product simpler to produce than conventional plywood. From this analysis it is possible to conclude that a proper selection of the wood type could potentially reduce the environmental impacts of furniture.

The LCA results of the bunk bed are also compared with the results disclosed by (Bambino, 2020), who adheres to the EPD (see Fig. 6). The furniture is based on beech wood and comprises two cradles; a cabinet and a chest of drawers (see Supporting Information, **Table S30** for the composition). Such examples are selected because to the best of our knowledge, no additional LCA that adheres to the EPD used in this work are publicly available. In addition, such comparison helps to understand whether or not the commercialized bunk bed by Muebles LUFE here studied is environmentally preferred over other commercial furniture. The impacts of the bunk bed are similar to the results reported for the

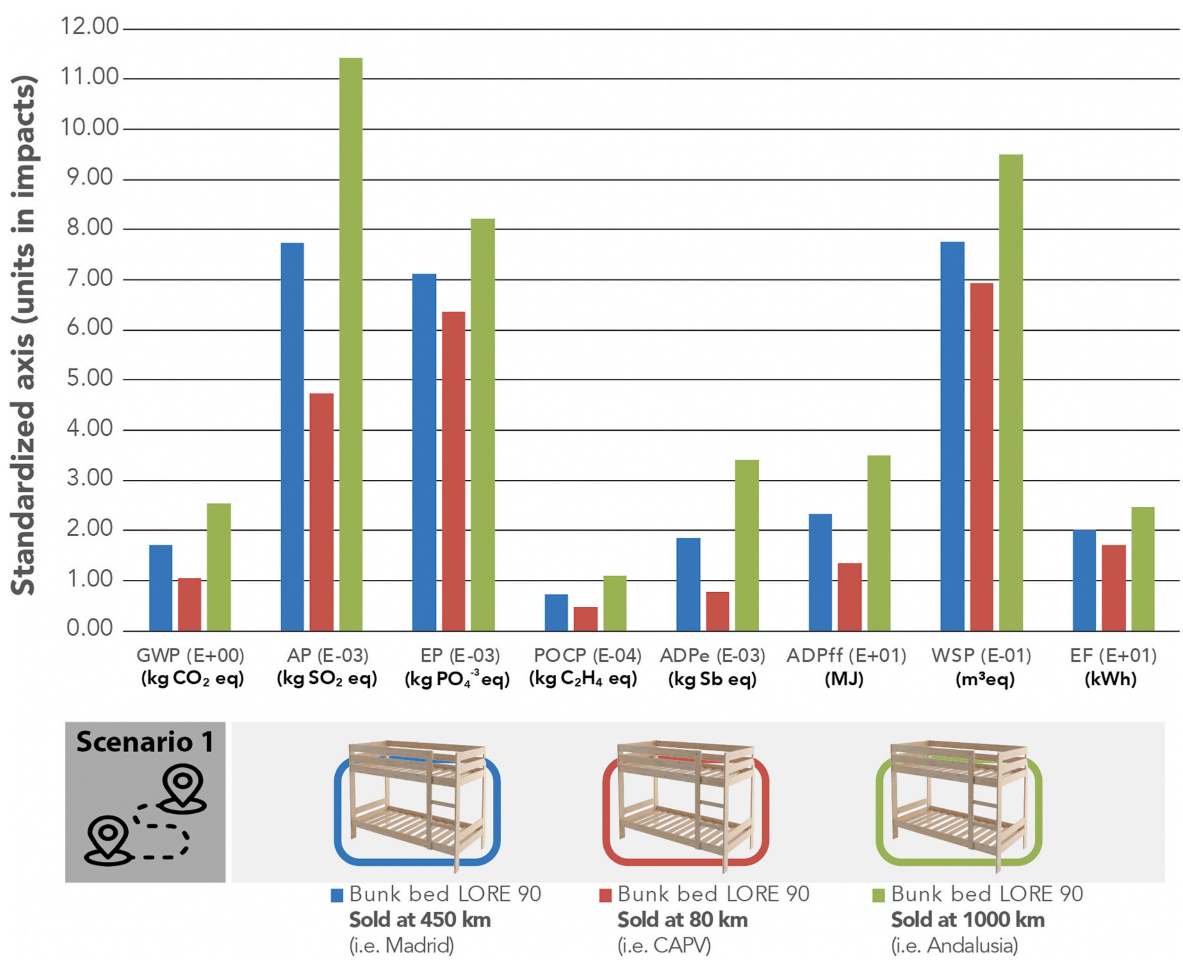

Fig. 7. Comparison of the environmental impacts of the LORE 90 bunk bed for Scenario 1: different distances to the end customer. Base scenario considers: 70 km between wood-source and manufacturer, 450 km between manufacturer and sales-site, 15 year lifespan, and EoL for the bunk bed and its packaging.

two cradles, while they are markedly below the impacts shown for the cabinet and the chest of drawers. For example, the GWP of the two Bambino cradles are 0.4 and 14.1% below the LORE 90 bunk bed, while the GWP reported for the cabinet and the chest of drawer is 133.4% larger (Table S31). To explain these differences, we should turn our attention to the furniture composition. It should be noted that the two cradles are composed of 90–95% solid timber, while the cabinet and the chest of drawers is mainly composed by beech plywood. These results agree well with the impacts shown in section 3.1., and suggest that the higher the content of solid timber, the lower the overall environmental impact may be.

Besides of the furniture composition, additional aspects should be also considered. In fact, while the two cradles are manufactured in the Italian Republic, the cabinet and the chest of drawers are manufactured in Bosnia and Herzegovina. When paying attention to the electricity mix of both countries (see Supporting Information, Table S32), it is possible to realize that the environmental impacts of the Bosnia and Herzegovina energy mix are notably above the results obtained for the Italian energy mix. Differences reach a maximum of +1387.2% for the eutrophication potential category. Therefore, with these data it can be stated that the difference between the environmental impacts of the two energy cradles of Bosnia and Italy is higher than for Italy. Therefore, we conclude that the variance between the environmental impacts of furniture is due both to the origin of the wood and the use of different energy configurations.

3.3. Local and international market scenarios

Once the impacts of the LORE 90 bunk bed are defined, a sensitivity analysis has been designed with alternative scenarios (1 kg of bunk bed as FU) to identify future opportunities to reduce the environmental impacts in the furniture sector according to the wood origin, sales destination or manufacturing location. We identify *Scenario 0* as the current production process carried out by the manufacturer. The *Scenario 1* considers to limit the *cradle-to-grave* environmental impacts of the bunk bed hypothesizing the furniture is sold on the Spanish market, either close to the production factory (80 km transport) or in the southern extreme (1000 km transport). As depicted in Fig. 7, all the impact categories are reduced by −10.5 to 57.5% for the nearest market, while increases ranging from 15.4 to 85.1% are achieved when the bunk bed needs to be transported by road 1000 km (in comparison to the 450 km of the original study). When considering the GWP, the differences will be of −39.6% and +58.8%, respectively with 80 km and 1000 km. These results underline the pivotal role of the final transport to the end-users (Liljenström et al., 2021). For additional details considering the environmental impacts in the alternative scenarios the reader is referred to Table S33, while details on the energy modeling and impact distribution are given in Tables S34–S53.

In the *Scenario 2*, solid timber and plywood are imported rather than locally sourced. To that end, three cases are assumed with transport distances of 600, 1650 and 12696 km (50 and 46 by truck and 12600 by train). As summarized in Fig. 8., larger impacts are achieved with the distance from the wood origin to the mill, with increases of 7.9–46.3% for 600 km, 10.4–47.2% for 1650 km, and 12.1–62.1% for 12696 km (GWP change by +43.3, +45.0 and + 39.4%, respectively). These results are consistent with the findings of Mirabella et al., who noted that short supply chains of 70 km (vs. standard supply chains of 1550 km)

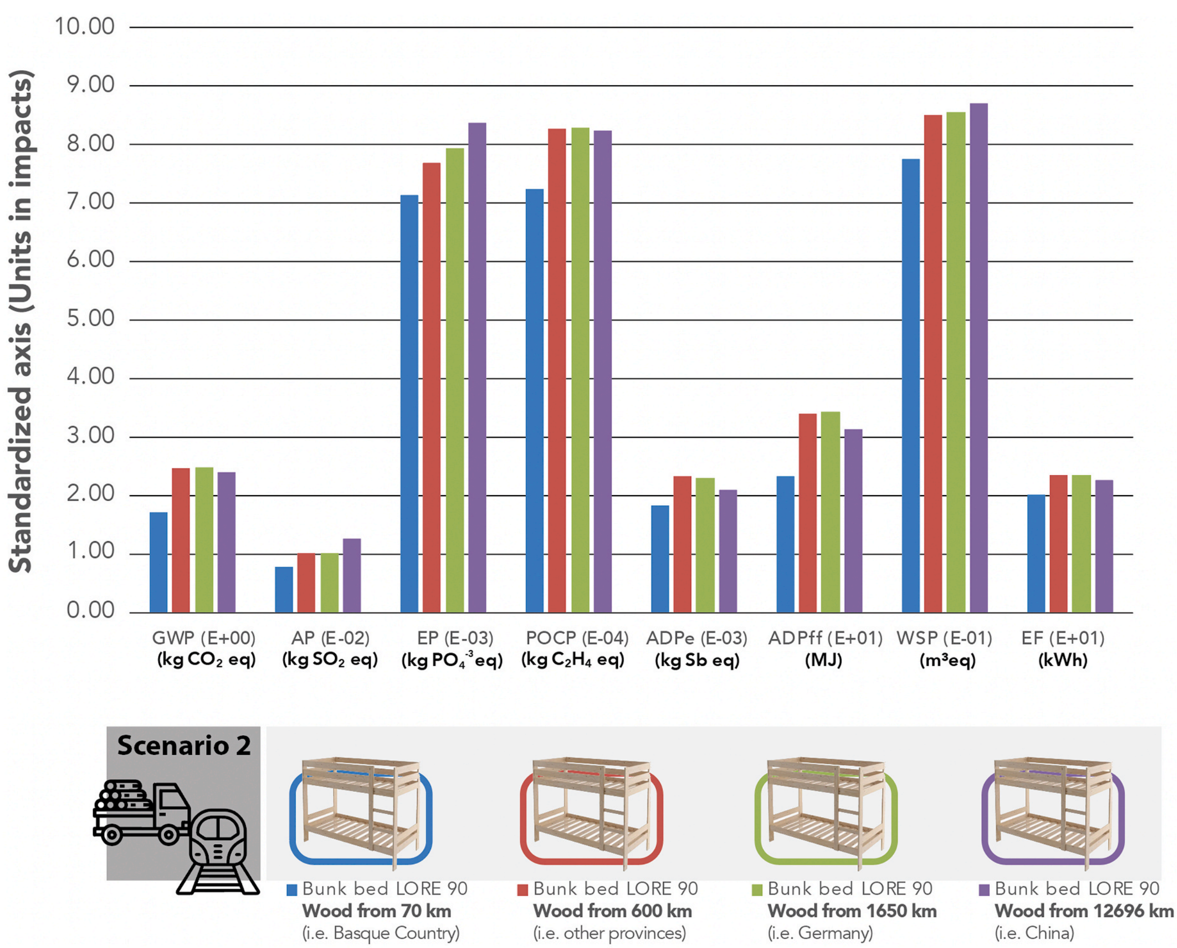

Fig. 8. Comparison of the environmental impacts of the LORE 90 bunk bed for Scenario 2: plywood is imported. Base scenario considers: 70 km between wood-source and manufacturer, 450 km between manufacturer and sales-site, 15 year lifespan, and EoL for the bunk bed and its packaging.

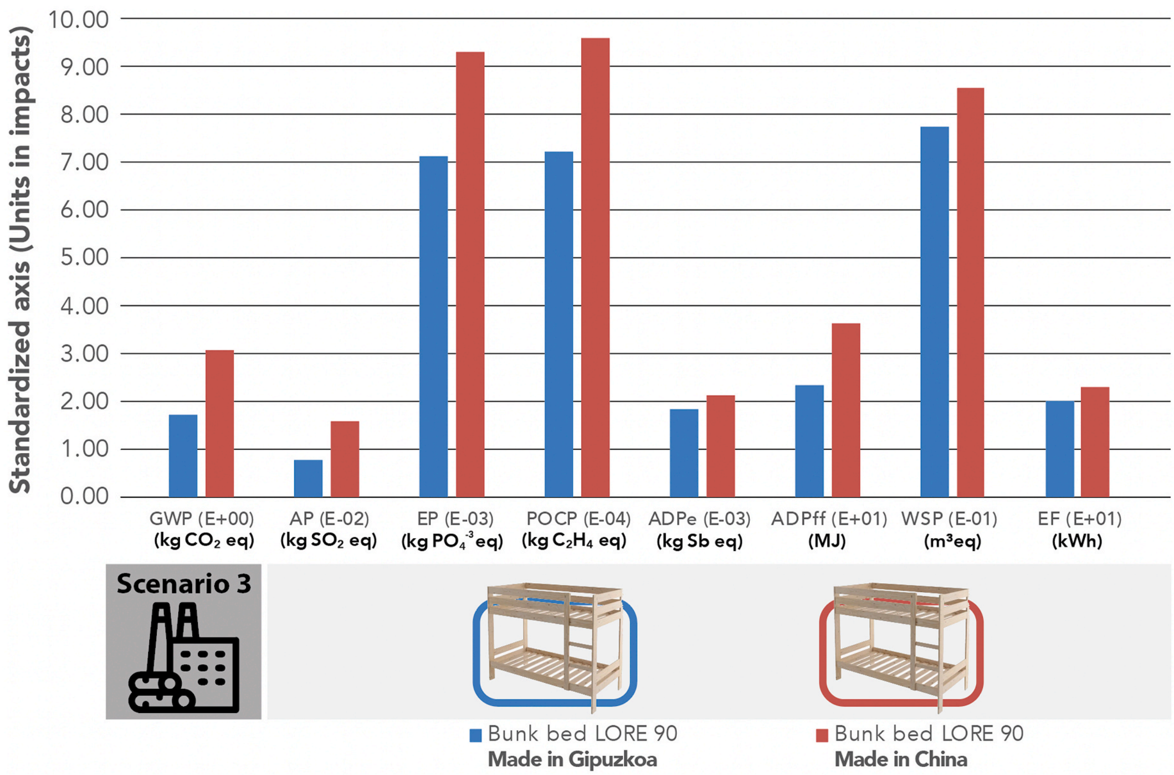

Fig. 9. Comparison of the environmental impacts of the LORE 90 bunk bed for Scenario 3: the bunk bed is manufactured in China and sold in Spain. Base scenario considers: 70 km between wood-source and manufacturer, 450 km between manufacturer and sales-site, 15 year lifespan, and EoL for the bunk bed and its packaging.

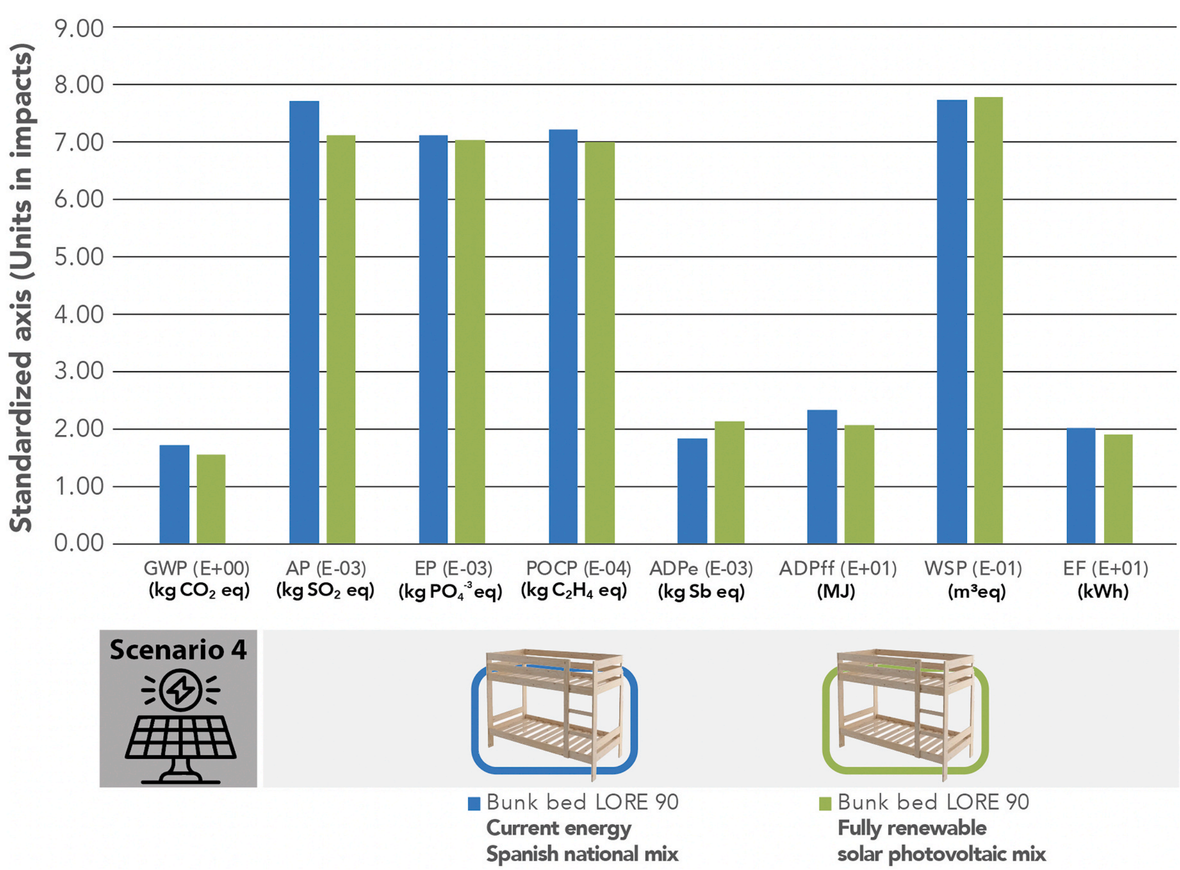

Fig. 10. Comparison of the environmental impacts of the LORE 90 bunk bed for Scenario 4: the bunk bed is manufactured using photovoltaic solar energy.

guarantee the minimization of impacts in all impact categories (Mirabella et al., 2014). However, the impact increase is not proportional to the distance covered as the bunk bed using wood originating from China has lower values in half of the impact categories (GWP, ADPe, ADpffP and EF) when comparing with the wood originating from Germany. These differences originate from the fact that the wood from China is estimated to travel by rail, while the wood from Germany is transported by truck. These findings agree well with the results reported by López de Lapuente Díaz de Otazu et al. for an industrial enzymatic cleaner production (de Lapuente Díaz de Otazu et al., 2021), who found reductions of 29% for abiotic depletion and 16% for GWP replacing a 100% road distribution by a railway transport. Considering the distance difference between Germany and China to LUFE mill, it appears that for a given distance, rail transport is preferred. Related information could be retrieved in the *"Transport and environmental report 2020, Train or plane?"* report that underlines the environmentally preferred profile of rail travel over plane or petrol/diesel-powered cars (European Environment Agency, 2020).

The *Scenario 3* shown in Fig. 9 analyzes the changes achieved when the bunk beds are fabricated in China and sold in Madrid, Spain. Therefore, the beds need to be transported for 12600 km by rail transport. Results reveal an increase on all the analyzed environmental impacts. More precisely, the impacts are increased by 10.5–102.9% depending on the category, where the GWP is enlarged by 79.4%. Such increases are ascribed to the impacts associated with the transport phase, which is a source of NO_x SO_x CO_2 emissions (Wan et al., 2016). Moving the production closer to consumers (from offshore production) may result thus an environmentally-friendly approach as the need for global freight (and associated energy and fossil-fuel consumption) is decreased. This conclusion matches the recommendation by Piekarski et al. (2017), who proposed the minimization of the existing distance between wood suppliers and manufacturing site to reduce the impacts of medium-density fiberboard manufacturing in a Brazilian plant.

González-García et al. noted the energy use as a considerable contributor to the overall environmental impacts of the furniture sector (indoor and outdoor wooden products) in Spain (González-García et al., 2011a,b). Therefore, the *Scenario 4* focuses on how environmental impacts would change upon the implementation of a 100% photovoltaic solar energy during furniture manufacturing (Fig. 10). General reductions for all the categories are observed, which range from 1.1% to 11.1%. Nevertheless, increases of 16.1% and 0.7% are observed for the categories of ADPe and WSP, respectively. These changes originate from the construction of solar panels which requires materials contributing to the category total of abiotic resource depletion of elements (copper connectors, silver, tin, or lead) (Van Oers and Guinée, 2016). The larger reduction is seen in the ADPff category, diverging from the findings by de Lapuente Díaz de Otazu et al. (2021) where the implementation of renewable energy was mainly reducing the acidification potential of industrial enzymatic cleaners by 26%. In fact, an increase of the renewable energy share lessens the overall impacts of goods as the pollution-related environmental impacts (CO_2 emissions, freshwater ecotoxicity, eutrophication, or particulate-matter exposure) of electricity production are cut (Hertwich et al., 2015). However, the extent of reduction is relatively small due to the fact that the implementation of renewable energy only affects the *core* phase, which has indeed the lower contribution during the entire life cycle. Accordingly, future measures to be taken towards the implementation of environmentally sustainably furniture production processes should be preferably focused on *upstream* and *downstream* stages, with special attention to wood-source and transport.

To extract clear conclusions, the GWP obtained in all the analyzed scenarios are briefly summarized in Fig. 11. Two alternatives are envisaged to lower the environmental impacts of bunk beds; selling products within a domestic market reduces the impacts by 39.6%, while the implementation of photovoltaic renewable energy during the *core* phase can lower the environmental affections by 9.9%. This is a logic outcome since the transport to the end-user is one of the hotspots of furniture. It also adheres to previous *cradle-to-gate* LCA studies that reveal that the substitution of imported wooden products by locally-sourced ones lowers the environmental impacts of the furniture sector fabricated in Spain (González-García et al., 2011a,b). The commercialization of the bunk bed in the Andalusia market (south Spain, 1000 km from the manufacturer) has a GWP increase of 58.9%. This impact rise is above the results observed after importing wood from the exterior,

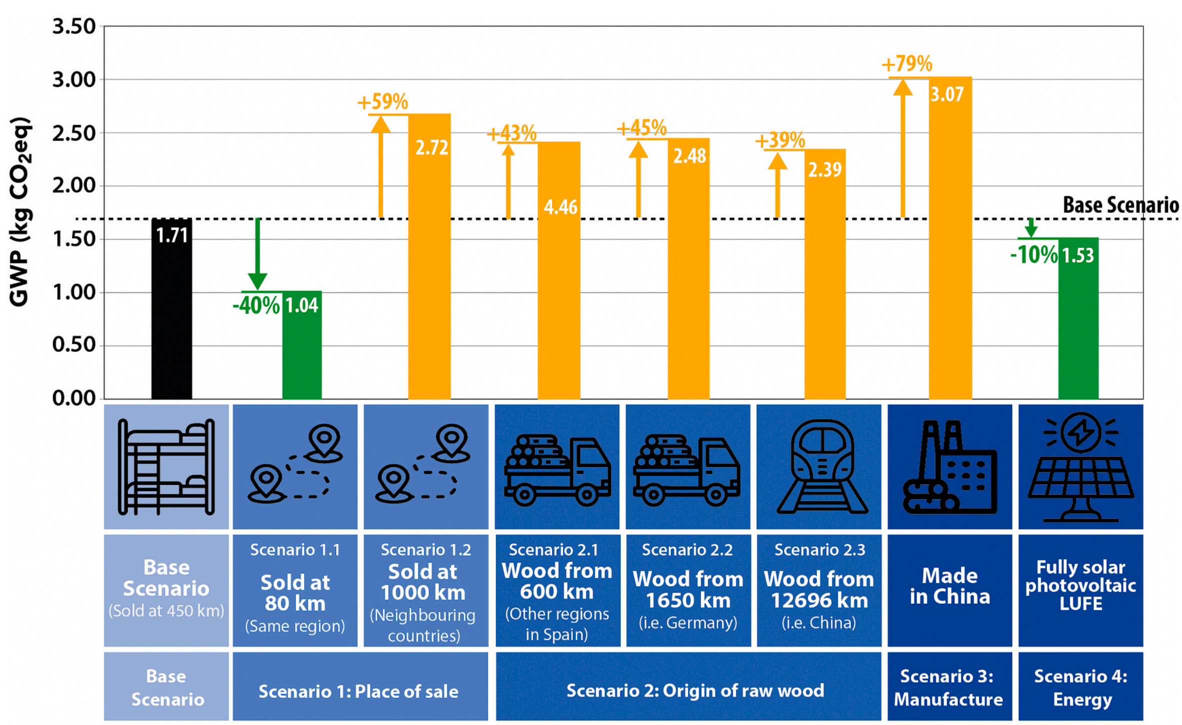

Fig. 11. Summary of the environmental impact changes for the alternative scenarios.

either from other regions in Spain (600 km by truck, 43.3% increase), from Germany (1650 km by truck, 45% increase) or China (12600 km by train, 39.4% increase). The fact that lower impacts are obtained for longer distances when rail transport is used (instead of truck) arises from the better energy-efficiency of rail over other means of network-based land transportation. In fact, during 2018, an average freight train presented a GWP of 18 g CO_2 per tone-kilometer, while the emissions of an average truck were 112 g CO_2 per tone-kilometer (Rail Freight). This lower impact is just a glimpse of the potential of rail in helping decarbonize the transport sector. Finally, with a 79.4% GWP value increase over the current fabrication conditions (*Scenario 0*), the less desired outcome is achieved when the LORE 90 bunk bed is manufactured in China and then marketed in Spain. Therefore, bringing the production back to locations near the end-users seems to be an effective strategy to transition towards sustainable production patterns.

Using a bunk bed as a representative example, this work sheds light on how eco-design and international market strategies determine the resulting environmental impacts of furniture. As the adoption of local materials notably reduces the energy and transportation needs (Morel et al., 2001), this work encourages the exploitation of locally-available resources, and local markets, in the furniture industry. Such sustainable production and consumption patterns could avoid the energy required for wood transportation, which notably contributes to the global warming, acidification and eutrophication (the major source of environmental impacts along the wood supply chain ranging from sawmills to final products are originated from the transportation of the wood from forest to the industrial manufacturing sites) (Adhikari and Ozarska, 2018). Although the results here obtained underline the environmental preference of minimally-treated wood over plywood, in the cases when the latter should be applied (for technical reasons, for instance), bio-refinery strategies could smooth the larger footprint of plywood. Cascading strategies that convert wood-residues into high added-value products are environmentally favorable over conventional wood extraction processes (Russell et al., 2022). Cascaded wood represents a partial solution to the increasing wood demand and limited fresh wood availability because it enhances the resource efficiency, saving up to 35% of fresh wood resources (Taskhiri et al., 2019). In this sense, it is particularly interesting to note that wooden furniture sector holds a prevalent position towards cascading among all the wood and bio-product industries (Husgafvel et al., 2018). However, it should be considered that wood modification (such as plywood fabrication) involves additional processing in comparison to un-modified wood, and this will be inevitably translated into an additional environmental impact. Therefore, a minimal processing of wood may be desirable for the furniture sector, always considering the trade-offs between further processing (which enlarge embodied impacts) and product durability.

Further considerations related to strengths and weaknesses of this work are worthy to note. The secondary data here used, together with the *cradle-to-grave* boundaries and PCR provide an accurate picture on the environmental sustainability of the wood furniture sector. However, although the sensitivity analyses enlarge the scope of the bunk bed studied, the results here shown are strongly local-dependent, making their extrapolation challenging. As highlighted by Mirabella et al. (2014), this is a commonly found obstacle when performing impact assessments in the furniture sector. The integration of LCA with additional dimensions regarding social and economic benefits originating from locally-sourced wood could provide the larger sustainability picture.

4. Conclusions

This work uses primary data to quantify the environmental *cradle-to-grave* impacts of a locally-manufactured wooden bunk bed according to the *"Furniture, except seats and mattresses"* Environmental Product Declaration. Using 1 kg of furniture as a functional unit, a global warming potential of 1.71 kg CO_2-eq is obtained. Importantly, this work considers primary data for the environmental impact assessment. The bunk bed here studied shows a 15.1% emission reduction in comparison with traditional furniture from the Ecoinvent v3.8 database. With a 53.1% share, we found that the plywood production is the environmental hotspot during the *upstream* stage. Regarding the *core* stage, the electricity consumption has the largest environmental load with a contribution of 75.1%. Finally, the transportation to the end-user bears the largest burden during the *downstream* phase, with a share as large as 82.6% regarding greenhouse emissions (17.8–98.0% share considering all the impact categories). Considering the entire life cycle stages, the *downstream* stage has the largest impact as it contributes to the 58.3% of the total greenhouse gas emissions (15.4–74.3% share considering all the impact categories). This result reflects the key role of large and heavy product transportation on the contribution tree of GWP in the furniture sector. Considering that plywood production is responsible for the 53.1–84.9% of the environmental impacts in the *upstream* stage, furniture based on solid timber may be preferred. In addition, the domestic manufacturing using local resources is encouraged as it reduces the need for transportation.

To study the potential to obtain environmentally wooden furniture, new scenarios are proposed by modifying selling location, raw material origin and manufacturing country. An additional scenario has also been designed including the origin of used energy. These new scenarios conclude the potential of localizing industrial processes: the sale of manufactured products in local markets (40% CO_2 reduction), the sale in markets that are 1000 km away (59% CO_2 increase), the use of imported wood that travels 600 km by truck (43% CO_2 increase), the use of imported wood that travels 1500 km by truck (45% CO_2 increase), the use of imported wood that travels 12600 km by train (39% CO_2 increase), the manufacture of the bunk bed in offshore locations (79% CO_2 increase), and the use of solar photovoltaic energy during production (10% CO_2 reduction).

Several lessons were learned in this work. Firstly, we found the *"Furniture, except seats and mattresses"* EPD incomplete as it does not account for the impacts generated during the use and end-of-life phases, where aspects such as durability, remanufacturability, recyclability or degradability are of especial concern. Accordingly, inaccurate results may be obtained as the complete life-cycle is neglected. Secondly, obtained data encourage wooden furniture producers to use local wood resources, to sell preferably in domestic markets and to implement renewable energies as a part of their electricity share. We expect these results may pave the way towards more environmentally sustainable practices by wooden furniture producers.

CRediT authorship contribution statement

Maider Coloma: Data curation, Formal analysis, Investigation, Methodology. **Ortzi Akizu-Gardoki:** Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Roles/. **Erlantz Lizundia:** Funding acquisition, Project administration, Validation, Visualization, Roles/.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2022.134795.

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