Science of the Total Environment 951 (2024) 175601

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Integrated sustainability assessment of wood building products: The case of larch and chestnut cascading systems in Northern Italy

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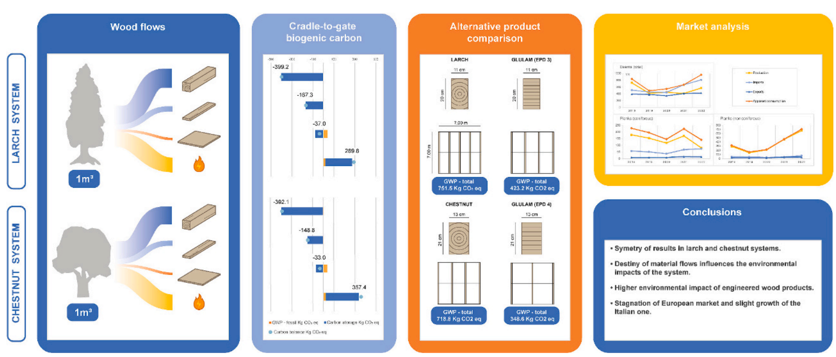
HIGHLIGHTS

- LCA and market analysis of larch and chestnut wooden products are discussed.
- Wood cascading material flows influence the overall sustainability of the systems.
- Cradle-to-gate GWP results in −314 and −205 kg of CO_2 eq due to carbon stored.
- End-of-life treatment greatly affects the results of GWP.
- Market analysis shows moderate decline for European and slight growth for Italian markets.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Jacopo Bacenetti

Keywords:
Biogenic carbon
Bioeconomy
Bio-based products
Material flows
Circular economy
Forest resources

ABSTRACT

Wood is increasingly being appreciated in construction due to its valuable environmental attributes. This paper explores the environmental and market performance of two wood supply chains in Northern Italy. Larch and chestnut wood are extracted and processed to obtain beams, planks, MDF panels and energy. LCA is performed to evaluate the environmental impacts of $1m^3$ of extracted wood through a cradle-to-gate approach. Then, a biogenic carbon analysis is carried out using the EN 16449:2014 standard including a comparison of different end-of-life treatments. Also, OSB is proposed as an alternative path for wood chips and contrasted to the current energy scenario. Moreover, solid wood beams and planks are compared with engineered wood products (EWPs). Lastly, a market analysis is conducted to assess the market trends of the different wood products studied.

The LCA shows similar results for both wood species across most impact categories, with slightly higher values for the chestnut system. Most impacts are related to the production of MDF boards and the energy valorization of wood chips. Biogenic carbon analysis shows a negative balance of emissions with −314 and −205 kg of CO_2 eq for larch and chestnut, respectively. It also suggests that OSB manufacturing can be a valuable alternative to the energy use of wood chips and that the end-of-life treatment with better results is recycling. The comparison of beams and planks with engineered wood products supports that solid wood poses a better environmental alternative in similar applications. Market analysis shows stagnation in the apparent consumption of wood

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https://doi.org/10.1016/j.scitotenv.2024.175601
Received 22 March 2024; Received in revised form 12 August 2024; Accepted 15 August 2024
Available online 16 August 2024

products in the European market and a slight growth in the Italian one between 2018 and 2022. Overall, the systems studied suggest that the potential environmental benefits of using wood in construction are not being matched by current market trends.

1. Introduction

Sustainability in buildings is a widely studied topic. Areas of study such as the circular economy and environmental analysis have increased in popularity in the built environment research in recent years (Eberhardt et al., 2022; Hossain et al., 2020; Lei et al., 2021). This is due to the considerable environmental burden that the construction sector involves, with about 28 % of the global GHG emissions attributed to buildings (IFC, 2019). Moreover, this sector is also accountable for consuming approximately 40 % of global raw materials each year, further accelerating the depletion of finite resources.

In response to these concerns, various environmental policies have been developed to address sustainability strategies for the construction sector, such as the European Green Deal (Bonoli et al., 2021; European Commission, 2021). Among these different options, one way to improve the environmental performance of buildings is through the use of bio-based materials. Novel bio-based materials are increasingly being studied due to their growing interest in order to meet emerging environmental requirements (Bumanis et al., 2020; Vinod et al., 2020). On the other hand, solid wood is a traditional construction material whose environmental benefits are well known (Cordier et al., 2022; Hill and Dibdiakova, 2016).

A key sustainability aspect regarding the use of wood as a building material is the offsetting of carbon emissions (Amiri et al., 2020). By storing relevant amounts of carbon over their service life, wood products are capable of turning buildings into carbon sinks, thus offsetting the carbon footprint of this sector. Timber elements are also well-suited to reduce the residues of their value chain since their cascading materials can be processed quite easily into other products, contributing to circular economy (Akadiri et al., 2012).

However, to achieve these benefits, it is essential that wood is sourced in accordance with the principles of sustainable management (Akadiri et al., 2012). These include, for example: conserving ecosystem services and implementing actions to maintain biodiversity; adopting a management plan that guarantees adequate forest regeneration; using silvicultural practices that are suitable for the tree species involved (FSC, 2023). This is often aligned with the social dimension of sustainability, as it contributes to establishing diverse value-added industries in fringe areas (Vierikko et al., 2008; Kuuluvainen et al., 2012). Furthermore, the growing market in the bioeconomy sector is an opportunity to further promote research on wood-based materials (European Commission. Directorate-General for Research and Innovation, 2018; Dams et al., 2023).

Therefore, enhancing fragile areas (i.e. areas with low population density presenting specific problems of isolation, abandonment, impoverishment, low participation and distant from the main centers of supply of essential services), where forest management is driven by economic reasons, is intrinsically linked to other key aspects of sustainability, such as social and environmental ones. Indeed, in fragile areas, such as mountainous ones, active forest management can contribute to the stability of slopes, fostering the livability of populated areas (García-Ruiz and Lana-Renault, 2011). Moreover, forest management also provides several ecosystem services, such as carbon storage, water regulation and tourist-recreational activities (Bruzzese et al., 2023), and sustains bio-based production supply chains that create stable jobs ranging from forest operations to wood processing and trade (Bruzzese et al., 2020).

In this study we analyzed the sustainability of a timber production supply chain within a north-western region in Italy. We explored the local processing of solid wood beams made of larch and sweet chestnut originating from sustainably managed forests, as well as the flows of the cascading products. The aim was to investigate the environmental and economic sustainability dimensions of these systems by conducting various analyses that address different aspects of sustainable timber production. Accordingly, the study comprehensively examines the environmental impacts, the potential for biogenic carbon storage, provides an insightful comparison of product alternatives, and a market analysis of the diverse range of products generated. The multifaceted nature of this investigation is key for assessing the overall viability of the system within the growing commitment to sustainable resource management and climate crisis mitigation.

2. Methodology

2.1. Case study

The subject of this study is the analysis of a larch (*Larix decidua* Mill.) and chestnut (*Castanea sativa* Mill.) supply chain in the northwest of Italy, specifically in the Piedmont region. These are the two main forest species present in the area, respectively for conifers and broadleaves, with the ability to provide structural timber assortments widely used in construction. As shown in Fig. 1, both species are present in this area, with less than 30 km of distance between the forestry sites and the sawmill concerned. Both forestry sites are managed in accordance with the PEFC (Programme for the Endorsement of Forest Certification) scheme to ensure the sustainability of the system and a legal supply chain. The forest operations are similar, with small differences such as the method of extraction: after felling, larch wood is yarded (extracted by cable), while chestnut wood is hauled by a wheeled tractor with a winch.

At the sawmill, both wood species undergo similar processing, as illustrated in Fig. 2. Firstly, the timber is sawn into squared-section solid beams which are then left to natural seasoning. Then, the raw planks obtained by cutting the beams are trimmed and their thickness is adjusted by planning. Wood chips are then obtained by processing the trimming wastes and branches through a wood-chipper, and are currently used for energy valorization purposes. Lastly, sawdust is sold for medium-density fiberboards (MDF) production. All processes described occur in the studied sawmill, except for the incineration of wood chips and the manufacturing of MDF boards.

2.2. Life Cycle Assessment

Life Cycle Assessment (LCA) provides useful insights into the sustainability of industries due to its comprehensive and systematic methodology used to evaluate the environmental impacts of products or processes throughout their entire lifecycle. This methodology is framed by ISO 14040 and ISO 14044 (International Organization for Standardization (ISO), 2006a; ISO, 2006b). LCA facilitates the quantification of various environmental indicators, enabling an accurate and holistic understanding of the environmental implications of construction products. It also aids informed decision-making and the development of sustainable construction practices.

LCA has been extensively applied to analyze construction products/systems in previous studies (Anand and Amor, 2017; Dias et al., 2021; Lei et al., 2021). This has led to the establishment of specific guidelines for assessing their environmental impacts, such as the standard EN 15804:2012 + A2:2020 (European Committee for Standardization (ECS), 2020). This standard provides a common framework for construction products to obtain an Environmental Product Declaration

(EPD), which is a type III ecolabel certification (ISO, 2006c). Following these standards is essential to ensure consistency and reliability in environmental assessments, allowing meaningful comparisons between construction products.

2.2.1. *Goal and scope*

This study aims to perform various analyses on the integrated systems of chestnut and larch wood production in the North of Italy. The current management practices for these wood types lead to a distribution of wood flows through the supply chain that vary between larch and chestnut products, leading to differences in environmental performance. Additionally, we seek to assess the environmental and economic viability of solid wood products compared to engineered wood alternatives. These analyses are based on the multifaceted issues mentioned in the Introduction:

- Process-based LCA is conducted on the cascade product system under study. This involves tracking the flows of wood materials throughout the manufacturing process to understand where the materials end up and to assess the relative environmental impact of the co-products.
- Biogenic carbon calculation is performed to understand the potential of wood construction products to counterbalance emissions generated during the manufacturing process and to contribute to the mitigation of climate change. This analysis is accompanied by an alternative route for woodchips, namely the production of Oriented Strand Board (OSB).
- A comparative analysis is conducted to identify alternative products with similar performance that could replace those within the studied system. This evaluation considers the mechanical properties of both the studied products and their alternatives. In this context, the term engineered wood products (EWPs) refers to a broad group of products made of wood components, such as layers or particles, and adhesives used to bond them together and/or with other materials (Bader and Omarsson, 2023); examples are glulam beams and plywood flooring.
- Lastly, a market analysis is used to evaluate the competitive landscape and positioning of the products from the system studied and the comparative analysis.

The system boundaries were defined to include all relevant processes associated with the system studied. These boundaries encompass activities ranging from the extraction of wood at the forest sites to the transportation to the processing facility and the manufacturing of the finished products. This includes the sawmill for solid wood products (beams and planks) as well as other processing facilities for engineered wood boards and energy valorization paths. This type of analysis is referred to as a cradle-to-gate LCA, with the stages studied representing A1 to A3 according to the standard EN 15804:2012 + A2:2020, also named as the product stage. The other stages are omitted due to uncertainty regarding the destination of the finished products.

2.2.2. *Functional unit*

In this research, system expansion is utilized to address the multifunctionality of the system. As such, a declared unit has been defined to account for the impacts based on the flow of wood used for each co-product. This unit entails $1m^3$ of round wood collected in the forest for processing. The use of a volume unit is a common practice within wood LCA studies (Sahoo et al., 2019; Dias et al., 2020; Duan et al., 2022). The objective is to establish a reference unit given the typical declared unit in LCA, which is calculated based on the volume of wood. Hence, a volume material flow is calculated for both wood types to determine the distribution of material within the multifunction system. The distribution of environmental impacts among the co-products in a multifunction system can be done through different allocation methods. In this research this is achieved through mass allocation, where the environmental impacts of the shared processes are proportionally assigned based on the mass of wood of the co-products.

Regarding the displacement analysis, different functional units were established to assess the numerous applications of the co-products. The functional unit for each product was defined based on the Product Environmental Footprint (PEF) methodology (Zampori and Pant, 2019). This functional unit defines what the product is meant to achieve, enabling the assessment of its environmental impact in relation to the specific function it delivers (Goldáraz-Salamero and Sierra-Pérez, 2023). It is fundamental for conducting consistent and comparable environmental assessments of various products. These functional units are discussed in the corresponding product displacement section.

2.2.3. *Life Cycle Inventory*

Primary data have been collected by monitoring and performing interviews for processes at the extraction sites and the sawmill. The main inputs for the processes include electric energy, fossil fuel, lubrication oil, raw materials and transportation. For the processes beyond the sawmill, secondary data have been used. The data for the MDF boards is retrieved from Nordboard Europe Ltd. (2022), while the Ecoinvent database process for wood incineration has been used for the energy valorization of woodchips.

For background processes, the Ecoinvent v3.8 database was used. However, the studied system involves small-scale production, which leads to the use of machinery not modeled in the Ecoinvent database. Furthermore, the contribution of machinery manufacturing is expected to be small compared to electricity and fuel consumption from wood processing. Consequently, the impact of the production of this machinery has been omitted. Moreover, since the studied forestry system comprises sustainably managed forests with autochthonous tree species, land use occupation and land use change have also been excluded. Therefore, it is considered that there is no significant change in the use of land or in the area from the activities analyzed in this study.

2.2.4. *Impact assessment*

There is usually a high degree of heterogeneity in the impact

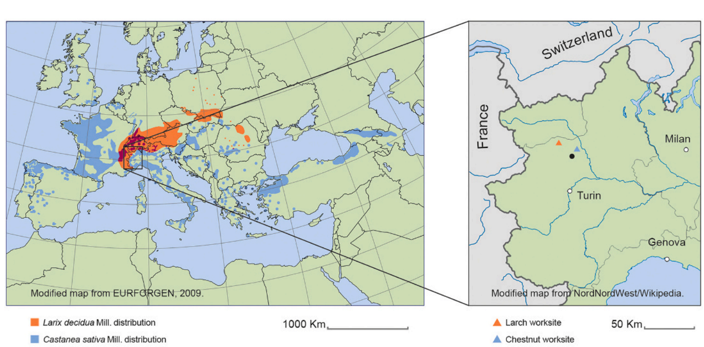

Fig. 1. a) Left: Distribution of larch and chestnut species in Europe and b) Right: location of the studied forest extraction sites and sawmill.

methods chosen for LCA studies of wood products. Methods such as Impact 2002+ (Mitterpach et al., 2022), ReCiPe (Laina Relaño et al., 2022; Sander-Titgemeyer et al., 2023), CML (Deng et al., 2023), IPCC and others are often used. Sahoo et al. (2019) found in their systematic literature review that TRACI, CML, Ecoindicator and ReCiPe are the most used impact methods in this research area. On the other hand, the EN 15804:2012 + A2:2020 guidelines establish specific parameters for the environmental analysis of construction products. To maintain consistency with the LCA of construction products and facilitate comparison with alternative products with EPDs, we have selected the corresponding EN 15804 method for this study, which is available in the LCA software SimaPro v. 9.4.0.3.

This method comprises standard environmental indicators such as global warming potential (GWP), which in this case is divided into four categories: fossil, biogenic, land use and land use change, and total. However, the biogenic carbon category has been calculated using a different method, as explained in the following section. Other impact categories adopted by this standard include ozone depletion potential (ODP), acidification potential (AP), freshwater eutrophication potential (FEP), marine eutrophication potential (MEP), terrestrial eutrophication potential (TEP), photochemical ozone creation potential (POCP), mineral resource scarcity (ADP - M), fossil resource scarcity (ADP - F) and water depletion potential (WDP). These categories were expanded in the revision of the standard to align with the European Product Environmental Footprint methodology. Following the method these categories were chosen to be analyzed in this study.

2.3. Biogenic carbon storage

In addition to the impact categories listed above, this study includes a calculation of the biogenic carbon stored by wood products. This aspect has become increasingly relevant over the last few years, given the contribution that wood products can make to mitigate climate change (Sierra-Pérez et al., 2016; Andersen et al., 2022). To this end, the carbon storage of the various co-products considered was calculated according to the standard EN 16449:2014 (ECS, 2014). This standard serves as a guideline to estimate carbon dioxide sequestration based on biogenic carbon stored. The calculation was made using the following formula:

$$P_{CO_2} = \frac{44}{12} \times cf \times \frac{\rho_\omega \times V_\omega}{1 + \frac{\omega}{100}}$$

where P_{CO_2} is the amount of carbon dioxide stored by the product; cf is the carbon fraction of wooden biomass (set to 0.5 according to the standard), ρ_ω is the density of wood at a given moisture content ω (taken from Ruffinatto et al., 2019), and V_ω is the volume of the product at that moisture content. For the considered wood species, larch and chestnut, the carbon dioxide sequestration for 1m^3 of wood at 12 % moisture content is 982 and 949 kg CO_2 eq·m^3, respectively.

The use of wood chips to obtain fiber for oriented strand boards (OSB) was hypothesized as an alternative to their energetic destination. The aim was to assess the potential benefits of prolonging the value and life span of the material, postponing the release of sequestered carbon from the incineration.

Furthermore, an end-of-life analysis has been performed to compare the outcomes of the alternative scenarios in which the wood could be processed after its service life. As a rule, the results of carbon emissions vary greatly if the end-of-life treatment is being considered. The different scenarios assessed were landfilling, incineration and recycling

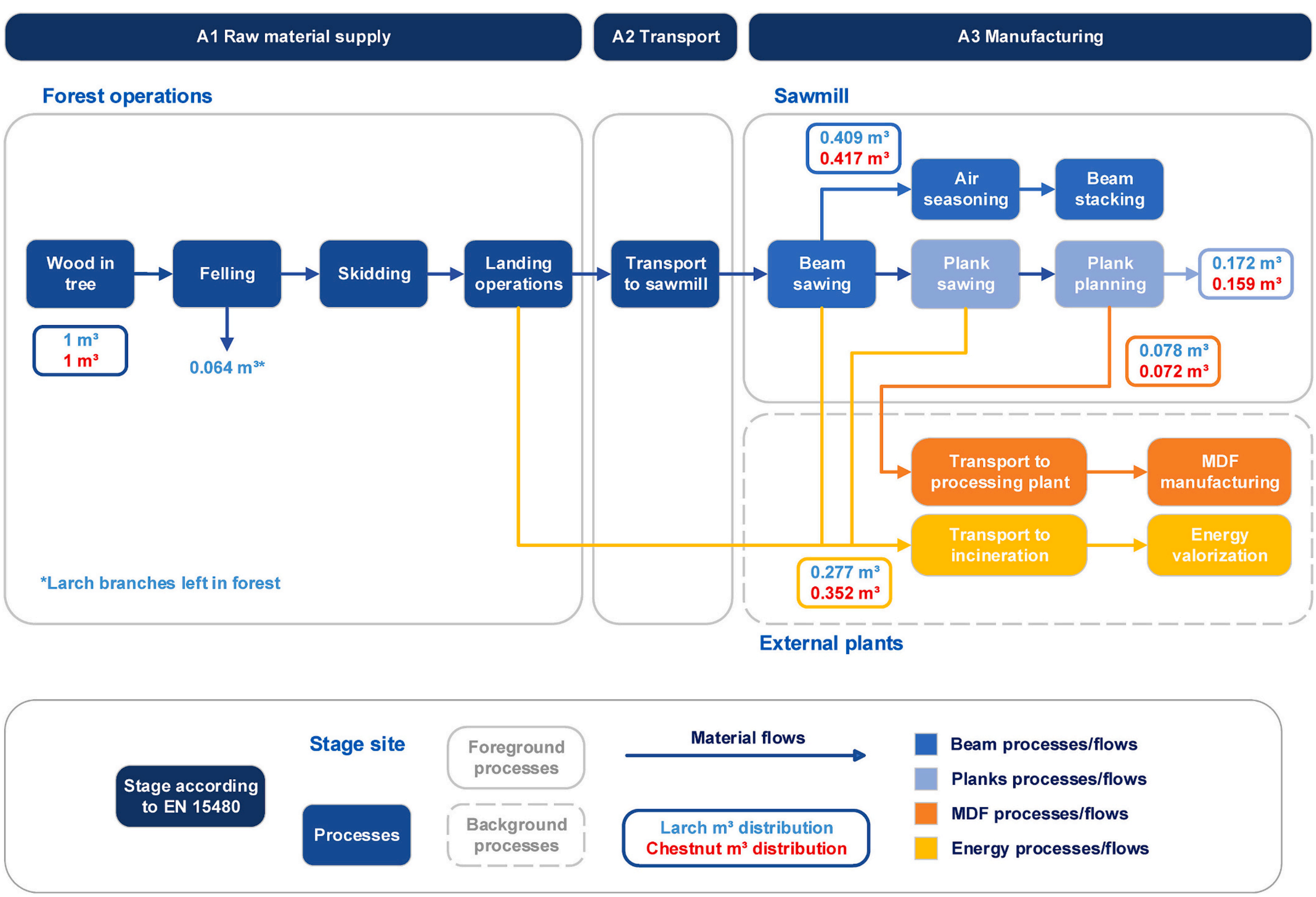

Fig. 2. System boundaries and material flows of the wood processing systems.

into a new product. A life span of 50 years was considered, which allows to reflect the delayed emissions of the incineration scenario through the calculation of a correction factor (British Standards Institute (BSi), 2011). Moreover, for the landfilling route, it has been considered that 98 % of the carbon is stored permanently in the wood, while the remaining 2 % is emitted over 20 years at a constant rate (BSi, 2011; Sierra-Pérez et al., 2016). Finally, in the recycling or cradle-to-gate scenario, the wood is reprocessed into a new product without material losses, in this case MDF boards. The life span of the wood products is amplified to 100 years, for which the PAS 2050 does not consider biogenic carbon emissions and only the manufacturing process emissions have been accounted for.

2.4. Alternative product analysis

Life Cycle Assessment not only serves the purpose of identifying the environmental hotspots within a manufacturing process, but also can be used to compare the sustainability of different products with shared functions (International Organization for Standardization, 2006a). In the construction sector, and more specifically regarding structural products, there is a variety of solutions that could be chosen for the same applications as assessed, varying in their materials and designs (Mascarenhas et al., 2023; Sierra-Pérez et al., 2018). As previously mentioned, wood products have the potential to offset carbon emissions. However, the use of timber products for construction has to face some limitations regarding their mechanical properties and the dimensions available, especially in the case of solid wood (Issa and Kmeid, 2005.

This study proposes a comparison of the environmental impacts of solid wood beams and planks with alternative engineered wood products. To make a proper comparison, the substitute products must perform the same functions and meet the same technical requirements as the original ones (Vadenbo et al., 2017). For that reason, the assessed products are compared under a same scenario of building application as part of a flooring system: planks for floor covering, and beams for flooring structure. In the case of the planks, we have compared them to plywood flooring, and the solid wood beams are compared to glue laminated (glulam) timber.

To assess the impacts of the alternative products, we selected existing EPDs, which were also drafted according to the framework of the EN 15804 standard. Different approaches were used when selecting the FU for each comparison scenario:

- A FU of $1m^2$ was selected for comparing the solid planks with plywood flooring. This choice aligns with the FU used in the EPDs to enable a direct comparison between alternatives.
- For the comparison of the solid beams against glulam beams, a joist structure was proposed for a more accurate assessment of their function in meeting the same strength requirements. Accordingly, the FU was defined as m^3 of beams required to support the same structure.

The joist structure has been designed to meet the specific requirements of a realistic scenario where the wooden beams would be utilized:

- Structure requirements: for use in a residential building and to cover the dimensions of 7 × 7 m (49 m^2). The elements supported by this structure include a wood board of 1.5 cm thickness, a 5 cm concrete layer, and a flooring.
- Beams cross-section: in the case of the solid wood beams, we have considered the average sections produced at the sawmill: 11 × 20 cm for larch and 13 × 21 for chestnut. As for the glulam beams, they were proposed to have the same section as the solid timber counterparts.
- Wood resistance: the strength classes of the wooden beams according to EN 14081-1 and EN 14080 were used to identify the mechanical properties of the different beams (ECS, 2013, 2019). These classes are C22 for larch beams, C24 for chestnut beams and GL30 for both laminated beams.

With all these elements, the number of beams required has been calculated for each solution based on the distance of the positioned beams as seen in Fig. 3.

3. Results

3.1. Life Cycle Inventory

Table 1 shows the results of the inventory analysis by wood coproduct. The results of this analysis depict overall symmetry of the results between the tree species. In terms of the wood flows, the biggest flow is located in the wood beams, which account for around 40 % of the roundwood. The order of the rest of coproducts by volume of wood content would be energy recovery, planks and MDF boards. There is an 8 % greater volume destined for energy recovery from chestnut than from larch. Both wood types have less than 8 % of wood that goes into MDF manufacturing.

Regarding the other inventory elements, they are also generally similar for both wood types except for fossil fuel consumption. The chestnut system shows an increased use of fuel, due to the differences of extraction methods of the tree species, hauling by winch in the case of chestnut and yarding for the larch.

3.2. Life Cycle Impact Assessment

In Fig. 4, we can see a clear comparison of the distribution of impacts between the larch and chestnut systems. It is notable that the majority of the impacts for both woods are related to the energy valorization of wood chips and the manufacturing of MDF boards. MDF board production accounts for 82.5 % and 58.2 % of the impacts in the ODP category, and 69.3 % and 60.5 % in the ADP- F category for larch and chestnut, respectively. On the other hand, the energy valorization of wood chips contributes up to 68.7 % and 73.5 % of the impact in the AP category and 86.4 % and 89.5 % in the ADP - M category for larch and chestnut, respectively. The remaining operations exhibit a range of environmental impacts between 10 % and less than 1 % for most categories, which are especially low in the material extraction, transportation and plank production stages.

Tables A.1 and A.2 of the Appendix A from the Supplementary materials display the results of the LCA of $1m^3$ of roundwood of larch and chestnut, respectively.

3.3. Biogenic carbon

The results of the biogenic carbon analysis are presented in Table 2. Solid wood beams, planks, OSB boards and MDF boards show negative values for the calculation of the carbon balance, while energy valorization is the only coproduct with positive biogenic carbon emissions due to the release of carbon during the incineration process. In Fig. 5, it is depicted that beams and planks have the lowest values for carbon emissions for the production process. Furthermore, the beams have the highest carbon storage potential. This is directly related to the quantity of wood mass in the product when every other factor is the same.

On the other hand, OSB has the highest environmental impacts among the products compared. However, the carbon content of the boards makes them the product with the second-highest carbon content, with a total balance of −217.4 and −266.6 kg of CO_2 eq for larch and chestnut, respectively. Additionally, MDF boards have higher manufacturing emissions and a lower wood content compared to the other by-products. Consequently, this results in a carbon balance that, while still negative, is significantly higher than their counterparts, with −37.0 and −33.0 kg of CO_2 eq.

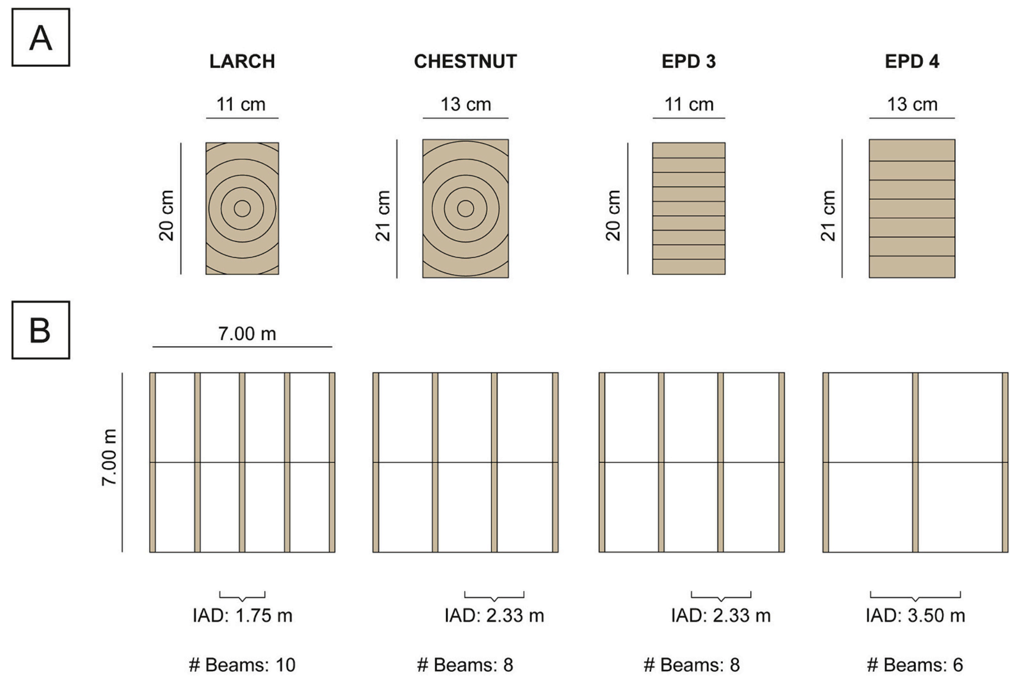

Fig. 3. A) Compared beam's solutions sections. B) Corresponding joist structure for each alternative. IAD: Inter-Axis Distance.

Table 1
Main Life Cycle Inventory inputs and outputs for larch and chestnut wood by $1m^3$ of roundwood.

Co-product	Input/output	Unit	Wood type	
			Larch	Chestnut
BEAMS	*Inputs*			
Primary data	Wood	m^3	0.409	0.417
	Fuel	g	655.6	1023.5
	Lubricant oil	g	53.2	63.4
	Transport	tkm	10.4	10.0
	Electricity	kWh	7.1	9.4
PLANKS	*Inputs*			
Primary data	Wood	m^3	0.172	0.159
	Fuel	g	277.3	377.4
	Lubricant oil	g	21.8	23.5
	Transport	tkm	4.4	3.8
	Electricity	kwh	5.7	6.1
MDF BOARDS	*Inputs*			
Primary data, Nordbord Europe Ltd. (2022)	Wood	m3	0.079	0.072
	Fuel	g	125.7	170.9
	Lubricant oil	g	9.9	10.7
	Transport	tkm	3.2	2.8
	Electricity	kwh	48.9	44.3
	Resin	kg	4.1	3.7
ENERGY VALORIZATION	*Inputs*			
Primary data, Waste wood, untreated {RoW}| heat production, untreated waste wood, at furnace 1000–5000 kW | Cut-off, U	Wood	m^3	0.277	0.353
	Fuel	g	446.5	849.8
	Lubricant oil	g	73.8	95.0
	Transport	tkm	27.0	33.0
	Electricity	kwh	19.4	21.6
	Outputs			
	Biogenic carbon dioxide emissions[a]	kg	307.0	335.1

Note: In the larch material flow, there is 0,064 m^3 of wood missing from branches that are cut-off and left in the forest.
[a] Biogenic carbon emissions calculated according to EN 16449:2014 (more information can be found in the biogenic carbon analysis section in this paper).

The results for the chestnut biogenic carbon analysis are consistent with the outcomes for larch. The values for carbon balance are negative for beams, planks, OSB boards and MDF boards, and positive for energy recovery. The GWP for energy recovery is slightly higher than that for larch, because there is more wood destined for this route in the chestnut system. Additionally, beams production also has slightly higher carbon emissions than in the case of larch, with a difference of 1.32 kg of CO_2 eq, and the biogenic carbon storage results in a marginally higher carbon balance by 6.00 kg of CO_2 eq.

Regarding the end-of-life analysis, Table 3 displays the results of the outcomes depending on the scenarios considered. For both larch and chestnut systems, the incineration route shows the highest carbon emissions, with over 500 kg of CO_2 eq emitted in the process. The landfilling scenario results in a negative carbon balance for both products, with −212 and −108 kg of CO_2 eq for the larch and chestnut systems, respectively. The recycling scenario yields the most favorable outcomes in both instances, resulting in a total carbon balance of −226 and −187 kg of CO_2 eq after the second processing for larch and chestnut, respectively.

3.4. Alternative products comparison

Table 4 illustrates the results of the comparison among the various flooring solutions. However, it is important to note that there may be discrepancies between the findings of this study and the environmental assessments presented in the EPDs.

The impacts for the analyzed categories are higher for the engineered wood floors from the EPDs, exceeding by 90 % of impacts for most of the categories except ODP and ADP – M. With respect to the biogenic carbon category, all four flooring products exhibit similar results with negative emissions of −21.80, −20.90, −27.50 and −18.70 kg CO_2 eq for larch, chestnut, EPD 1 and EPD 2, respectively. Consequently, all products have a negative balance of the GWP, albeit with a higher proportion for solid plank flooring, due to lower emissions associated with the production process.

In the analysis of solid and glulam beams, Table 5 presents varying results across the impact categories. The impacts from glulam beams are considerably higher for GWP – fossil, GWP – luluc, AP, MEP, TEP, POFC, ADP – F and WDP. Conversely, both solid wood beams exhibit higher impacts in the ODP category, particularly noticeable for chestnut beams with 85 % difference compared to larch beams, and the ADP – M

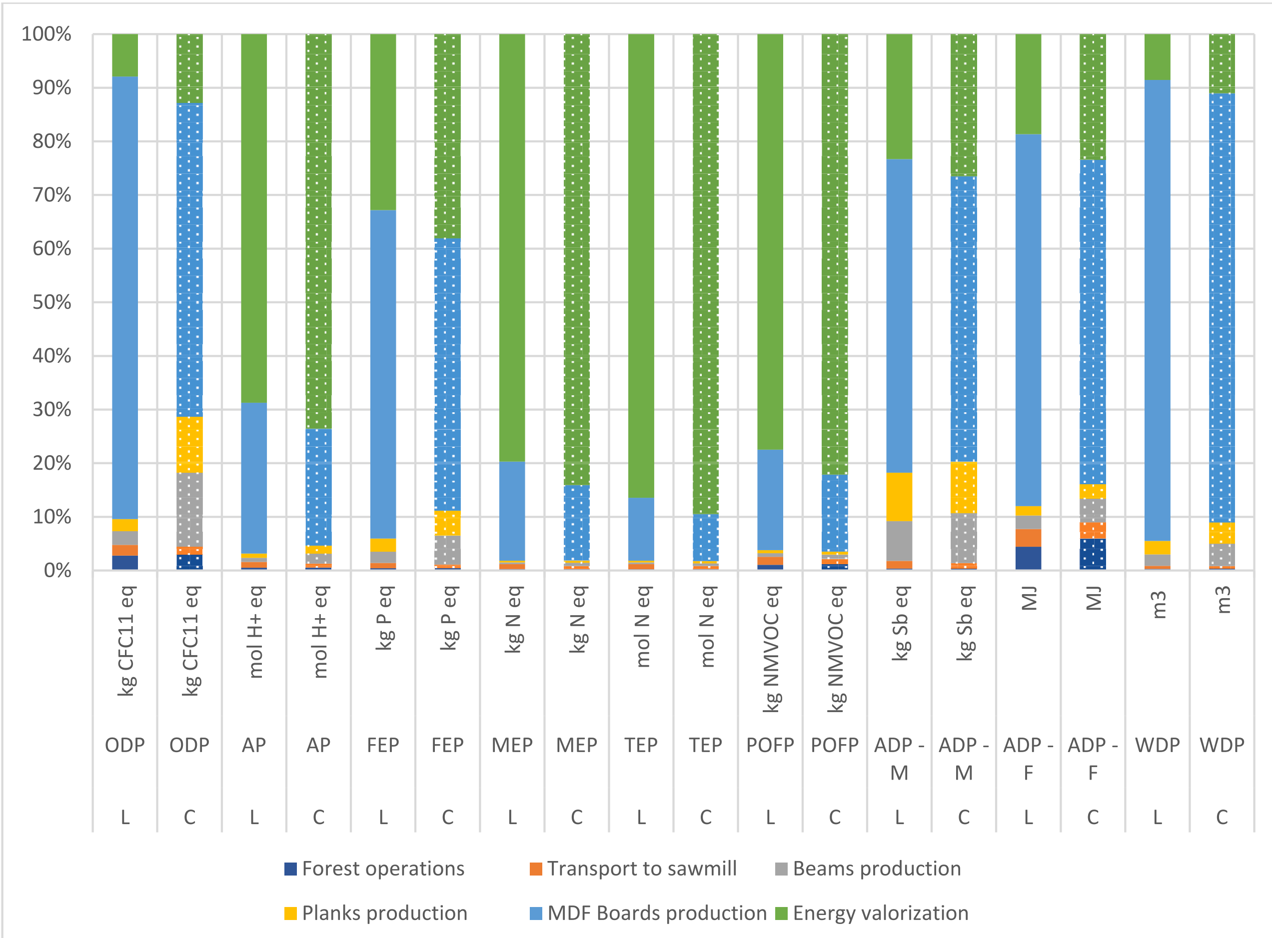

Fig. 4. Environmental impacts of larch (L) and chestnut (C) systems by stage. GWP categories have been omitted in this graph for further discussion in the biogenic carbon analysis section.

Table 2
Carbon balance results for cradle-to-gate stage of 1m^3 of roundwood by coproduct.

		Unit	Beam	Planks	MDF Board	Energy	OSB Board
	GWP - fossil	kg CO_2 eq	2.48E+00	1.63E+00	3.96E+01	1.78E+01	5.47E+01
Larch	Carbon storage	kg CO_2 eq	−4.02E+02	−1.69E+02	−7.66E+01	2.63E+02	−2.72E+02
	Carbon balance	kg CO_2 eq	−3.99E+02	−1.67E+02	−3.70E+01	2.81E+02	−2.17E+02
	GWP - fossil	kg CO_2 eq	3.80E+00	2.37E+00	3.53E+01	2.23E+01	6.76E+01
Chestnut	Carbon storage	kg CO_2 eq	−3.96E+02	−1.51E+02	−6.84E+02	3.35E+02	−3.34E+02
	Carbon balance	kg CO_2 eq	−3.92E+02	−1.49E+02	−3.30E+01	3.57E+02	−2.67E+02

category. The FEP category shows heterogeneous results between solid and glulam beams, with EPD 3 having the highest environmental impacts, followed by chestnut beams with 15 % fewer impacts, then EPD 4 and larch beams with approximately 65 % fewer impacts than EPD 3 each. It is noteworthy that in this analysis the GWP – total category demonstrates better results for solid wood beams, with differences ranging from 296 to 403 kg of CO_2 eq of carbon balance compared to glue laminated beams.

It should be noted, as a limitation of this study, that although the EPDs were selected to utilize the same impact method, the inventories may have been modeled differently from those of the systems assessed in this study.

The results of the environmental sustainability assessment were integrated with a market study to provide a more comprehensive analysis. The integration of these two lines of research provides a more cohesive and informed perspective. This link highlights the interaction between market dynamics and environmental sustainability, ultimately reinforcing the relevance and applicability of the results obtained on the case studies investigated.

3.5. *Potential market*

To analyze the market landscape of wood commodities, this research conducted an analysis to identify trends in consumption in both Italian and European regions. Apparent consumption from 2018 to 2022 of wood products was calculated for these markets, allowing for the measurement of the quantity of goods or services consumed over specific time period in a particular market. Apparent consumption is estimated using the following formula:

$$AC_i = DP_i + I_i - E_i$$

where AC stands for Apparent Consumption in a given year i; DP refers to domestic production; I is imports and E is exports.

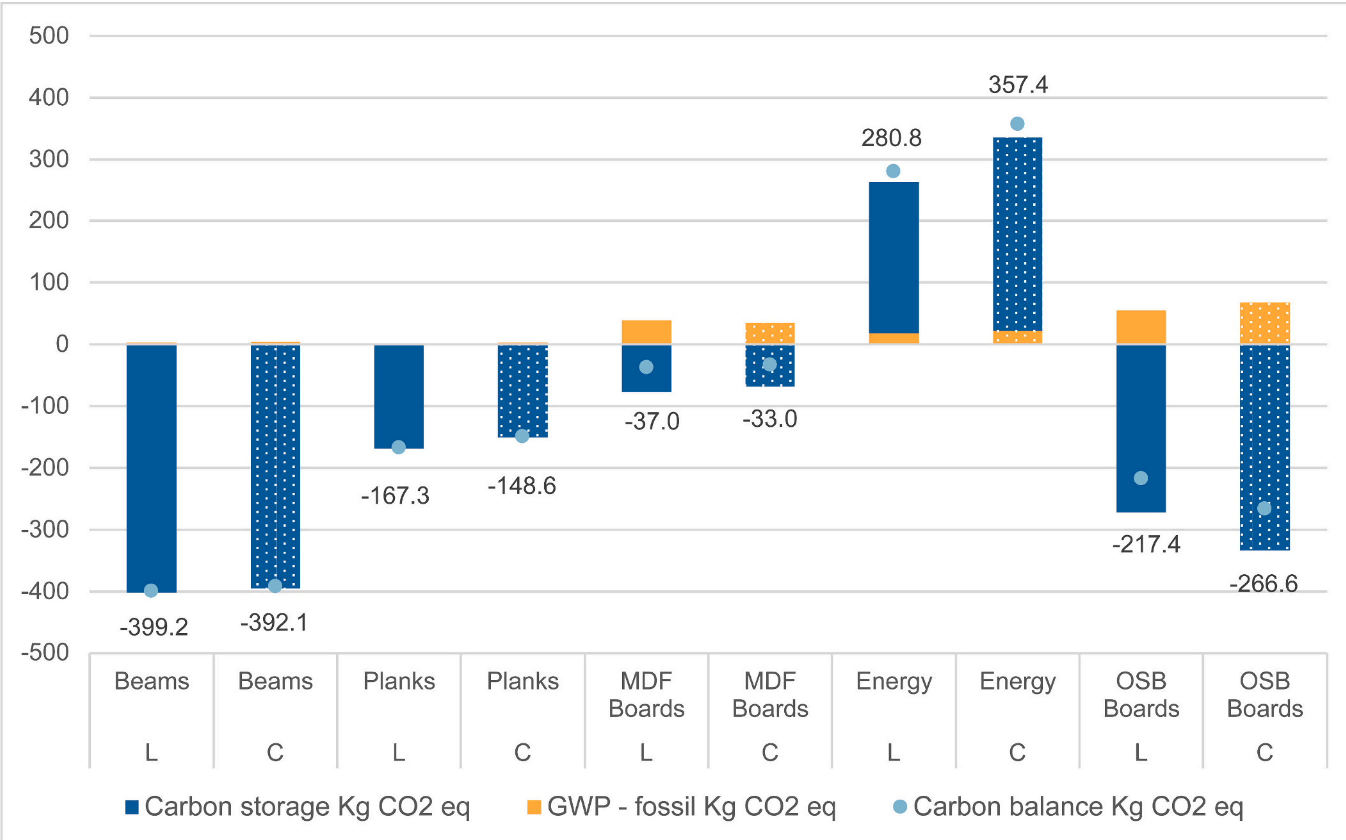

Fig. 5. Carbon balance results for cradle-to-gate stages of 1m^3 of roundwood by coproduct. The solid color columns correspond to the larch system and the patterned columns belong to the chestnut one.

Table 3
Biogenic carbon stored and emitted by the larch system for the end-of-life scenarios studied. The recycling route considers the reprocessing of the wood into MDF boards without material losses, for which the biogenic carbon stored is the same as the first product.

		Cradle-to-gate	Cradle-to-grave		Cradle-to-cradle	
			Incineration	Landfill	Recycling	
					First product	Second product
CHESTnut	Manufacturing emissions *(kg of CO_2 eq)*	6.15E+01	6.15E+01	6.15E+01	6.15E+01	4.21E+02
	Biogenic carbon emitted *(kg of CO_2 eq)*	2.72E+02	6.73E+02	3.23E+02	2.72E+02	–
	Biogenic carbon stored *(kg of CO_2 eq)*	6.47E+02	2.19E+02	5.96E+02	6.47E+02	6.47E+02
	Balance (kg of CO_2 eq)	−3.14E+02	5.16E+02	−2.12E+02	−3.14E+02	−2.26E+02
LARCH	Manufacturing emissions *(kg of CO_2 eq)*	6.38E+01	6.38E+01	6.38E+01	6.38E+01	4.28E+02
	Biogenic carbon emitted *(kg of CO_2 eq)*	3.47E+02	7.28E+02	3.95E+02	3.47E+02	–
	Biogenic carbon stored *(kg of CO_2 eq)*	6.15E+02	2.08E+02	5.67E+02	6.47E+02	6.15E+02
	Balance (kg of CO_2 eq)	−2.05E+02	5.84E+02	−1.08E+02	−2.05E+02	−1.87E+02

The data for Italian wood commodities were obtained from the ISTAT database (Istituto Nazionale di Statistica, 2023), while data for the European production was retrieved from the Eurostat database (European Institute for Statistics, 2024). Trade data from the UN Comtrade (United Nations Statistic Division, 2022) and Eurostat databases were also utilized. Although obtaining quality data for specific commodities and wood species presented challenges, the selected datasets have provided an overview of wood products and their market evolution.

The European market demonstrates a decline in apparent consumption across all examined products (Table 6), with the exception of glulam, where insufficient available data precludes a significant analysis. Production and imports of all products have decreased over the study period, while exports have either maintained stability or shown notable growth.

In Fig. 6. the results of the apparent consumption of wood products in the Italian market demonstrate heterogenous outcomes. Some commodities exhibit modest apparent consumption growth, while others display fluctuations over the studied years. The exception is the market for wood chips from non-coniferous trees, which shows stagnant

Table 4
Comparison of production of 1 m^2 of the larch and chestnut plank floors with the engineered flooring solutions from the EPDs. Sources for environmental impacts of the EPDs: EPD – 1 (Forestry Timber Export Sdn Bhd, 2023) and EPD – 2 (Forestry Timber Holdings Limited, 2023).

	Unit	Larch PLANKS	Chestnut PLANKs	Wood Engineered flooring - EPD 1	Wood engineered flooring - EPD 2
GWP - total	kg CO_2 eq	−2.14E+01	−2.06E+01	−1.18E+01	−2.20E+00
GWP - fossil	kg CO_2 eq	2.08E−01	3.28E−01	1.56E+01	1.64E+01
GWP - biogenic	kg CO_2 eq	−2.16E+01	−2.09E+01	−2.75E+01	−1.87E+01
GWP - luluc	kg CO_2 eq	1.82E−04	3.62E−04	7.34E−02	7.21E−02
ODP	kg CFC-11 eq	1.10E−08	5.47E−08	1.66E−07	1.80E−07
AP	mol H+ eq	1.09E−03	2.20E−03	1.06E−01	1.02E−01
FEP	kg P eq	6.12E−05	1.29E−04	2.31E−02	2.32E−02
MEP	kg N eq	2.12E−04	3.19E−04	3.13E−02	2.99E−02
TEP	mol N eq	2.20E−03	3.11E−03	2.91E−01	2.75E−01
POFP	kg NMVOC eq	1.12E−03	1.32E−03	8.37E−02	8.09E−02
ADP - M	kg Sb eq	5.52E−06	6.24E−06	1.51E−05	1.81E−05
ADP - F	MJ	4.44E+00	6.71E+00	1.68E+02	1.81E+02
WDP	m^3	1.06E−01	1.65E−01	2.04E+00	2.11E+00

Table 5
Environmental impacts of the different beam solutions for the selected FU. The scheme of the beams' frames is depicted above in Fig. 3. Sources for environmental impacts of the EPDs: EPD – 3 (Rubner Holding AG - S.p.A., 2023) and EPD – 4 (HASSLACHER Holding GmbH., 2021).

	Unit	Larch beams	Chestnut beams	Glulam - EPD 3	GLULAM - EPD 4
Beam section	m^2	0.022	0.027	0.022	0.027
# of beams	–	10	8	8	6
Volume	m^3	0.77	0.76	0.62	0.57
GWP - total	kg CO_2 eq	−7.52E+02	−7.19E+02	−4.23E+02	−3.49E+02
GWP - fossil	kg CO_2 eq	4.68E+00	6.96E+00	4.69E+01	8.26E+01
GWP - biogenic	kg CO_2 eq	−7.56E+02	−7.26E+02	−4.70E+02	−4.32E+02
GWP - luluc	kg CO_2 eq	3.08E−03	6.24E−03	1.58E−01	4.48E−01
ODP	kg CFC-11 eq	2.38E−07	1.03E−06	1.58E−09	3.92E−08
AP	mol H+ eq	2.14E−02	4.17E−02	4.00E−01	3.82E−01
FEP	kg P eq	8.97E−04	2.09E−03	2.46E−03	9.40E−04
MEP	kg N eq	4.86E−03	6.88E−03	1.61E−01	1.69E−01
TEP	mol N eq	4.96E−02	6.66E−02	1.42E+00	1.73E+00
POFP	kg NMVOC eq	2.92E−02	3.48E−02	4.79E−01	4.86E−01
ADP - M	kg Sb eq	7.12E−05	8.36E−05	2.59E−05	2.18E−05
ADP - F	MJ	1.22E+02	1.76E+02	6.47E+02	1.20E+03
WDP	m^3	1.45E+00	2.49E+00	1.55E+01	6.71E+00

production and imports, alongside a rapid increase in exports. This trend results in negative values for apparent consumption in 2021 and 2022.

4. Discussion

The life cycle assessment of 1m^3 of roundwood from larch and chestnut resulted in similar total environmental impacts, which was expected, given the similarity of the inventory analysis. The calculated environmental impacts of the chestnut system are higher for most categories, potentially correlated with the lower efficiency of the production process. In general terms, solid wood products like beams have lower environmental impact than MDF boards, attributed to their simpler processing (in particular, MDF and OSB production processes encompass reduction in smaller elements, artificial drying and pressing) and lack of adhesives. In fact, petroleum-based adhesives, depending on their amount and type, strongly affect impact categories of wood-based products (e.g. global warming, acidification, eutrophication and toxicity), hence the growing interest in bio-based adhesives suitable for the wood sector (Eisen et al., 2020). In addition, utilizing local timber can markedly reduce the overall GWP of wooden products and buildings, considering the emissions associated with the transportation (Atnoorkar et al., 2024). For instance, Liang et al. (2020) found that sourcing Cross Laminated Timber across the United States could result in global warming impact up to four times greater than sourcing timber within a state.

The increase in volume (+8 %) of chestnut destined to energy recovery can be attributed to the lower sawing yield of chestnut, which is also linked to the sympodial conformation of the trunk, whereas larch is monopodial. Another element was the decision not to collect larch branches for chipping, but rather leaving them at the extraction site. It is noteworthy that the production process of the sawmill could be optimized by adopting innovative roundwood grading technologies and enhancing sawing flexibility (Forghani et al., 2024). This optimization would result in increased sawing yields, thereby maximizing efficiency and profitability, and ultimately, positively impacting the carbon storage of the considered flows.

Biogenic carbon analysis revealed that numerous factors influence the outcomes in a bio-based multifunctional system like the one under study. As a fundamental parameter, when all other factors are equal, larch and chestnut wood store a similar amount of carbon, due to their comparable density. Overall, the study's findings confirm that products made of solid wood exhibit higher overall carbon efficiency, compared to wood-based engineered products. Nonetheless, engineered wood products can be derived from material that would otherwise be treated as waste. This is particularly significant in Italy, as it leads European countries with a 42 % share of waste wood being recycled for panel production (Nguyen et al., 2023). Additionally, the end-of-life scenario considerably influences the carbon balances of the studied systems. For instance, Farjana et al. (2023) analyzed scenarios for waste MDF and particleboard, determining that material recovery is advantageous over energy recovery for most impact categories, but energy recovery is preferable for climate change and fossil fuel depletion.

The comparison of flooring solutions revealed, as anticipated, that solid planks have significantly lower environmental impacts than engineered wood flooring across most categories, while carbon storage remains similar. This finding holds relevance considering that wood flooring can constitute a substantial portion of the total volume of wood furniture in apartments, thus exerting a considerable influence on the

Table 6
European apparent consumption evolution of the studied wood commodities between 2018 and 2022. Values presented in thousand cubic meters. Source: author's estimation with data retrieved from Eurostat and UN Comtrade databases.

	Production					Imports					Exports					Apparent consumption				
	2018	2019	2020	2021	2022	2018	2019	2020	2021	2022	2018	2019	2020	2021	2022	2018	2019	2020	2021	2022
Sawnwood	222,800	223,156	216,543	105,688	88,684	48,472	48,156	46,903	59,390	38,002	4420	4327	4104	4885	9218	266,852	266,984	259,342	160,192	117,469
Glulam	N/A	N/A	N/A	4458	4276	N/A	N/A	N/A	N/A	1265	N/A	N/A	N/A	N/A	2702	N/A	N/A	N/A	N/A	2839
Plywood	4580	4567	3748	3317	3228	8357	8226	8129	8878	5205	4420	4327	4104	4885	9218	8517	8466	7773	7310	−784
MDF	12,782	13,282	12,517	12,808	10,174	6361	6631	6387	6950	4539	6980	8569	8686	9439	6690	12,163	11,344	10,218	10,319	8023
OSB	4468	3138	2168	2513	2116	4042	3601	4046	4027	3064	4136	4094	4015	3682	3573	4374	2645	2199	2858	1606
Wood chips	67,743	68,833	66,011	68,855	58,951	17,917	19,382	17,147	16,251	12,642	10,693	10,695	9694	9492	11,412	74,967	77,521	73,463	75,614	60,181

overall environmental impact and carbon storage (Negro and Bergman, 2019). However, engineered wood flooring boasts greater dimensional stability than solid wood flooring, an important technical requirement that influences product selection.

Regarding structural products, the lower GWP of solid timber is remarkable, particularly considering its competition with glulam in certain applications for which it would be entirely suitable, especially in small private residential buildings with limited span. In this context, the current European normative framework, which requires CE marking after visual or machine timber grading, enables solid structural timber to meet modern design criteria, thus presenting a viable alternative to non-wood and engineered wood-based products (Negro et al., 2013). Overall, solid wood products exhibit superior environmental performance compared to engineered wood products across most impact categories, primarily due to the absence of synthetic adhesives. This finding aligns with the expectations and is consistent with previous studies (Dias et al., 2020). However, it is to mention that engineered wood products can be used in applications unsuitable for solid timber, thereby circumventing the use of non-wooden alternative materials in construction, which typically entail higher environmental impacts.

The market analysis revealed a decline in European timber production between 2019 and 2022. This trend is consistent with data from the European Panel Federation (2023), which also indicated a reduction in the production of OSB and MDF during the same period. The UNECE/FAO 2022–2023 Forest Products Annual Market Review attributes the contraction of wood panels market to the decrease of demand due to the stagnation of housing construction and an "uncertain economic outlook". Conversely, the Federation's calculations show an increase in plywood panels production over the same timeframe. In Italy, the timber construction sector has exhibited steady growth in recent years, with a notable 33 % increase in turnover in 2022 compared to 2020 (Centro Studi Federlegno Arredi, 2023). This growth can be attributed to both the escalating interest in wood as a sustainable material and the diverse range of modern construction solutions offered by engineered wood-based products such as Cross Laminated Timber.

5. Conclusions

In this paper we analyzed two cascading product systems involving larch and chestnut, using the LCA methodology. A remarkable finding was that the environmental impacts of these systems are not solely determined by the wood content in the various products but are also influenced by the complexity and nature of the production processes. For instance, the environmental impacts of MDF board production constitute approximately 50 %–80 % of impacts for categories such as Ozone Depletion Potential and Acidification Potential, while energy valorization accounts for 60 %–80 % in Acidification Potential and Mineral Resource Scarcity. Nonetheless, material flow does impact biogenic carbon analysis, as carbon storage is directly proportional to the amount of material. Consequently, products with higher wood content and simpler manufacturing processes involving fewer auxiliary materials tend to offer greater environmental benefits. This aligns with the growing interest in wood in construction, as a means of enhancing building sustainability.

Moreover, this research underscores the significance of end-of-life treatment for wood products in comprehending the carbon balance and mitigation potential of bio-based products. The analysis performed suggests that solutions prolonging the lifespan of a product through recycling may positively impact carbon emission reduction. In this sense, designing wood products with maximum reuse and recyclability options is an effective strategy to promote the principles of a circular economy also in terms of a cascading approach. Additionally, the comparative analysis reinforces the notion that a detailed examination considering the product's function offers valuable insights into the environmental performance of wood products.

The market analysis, conducted by estimating the apparent

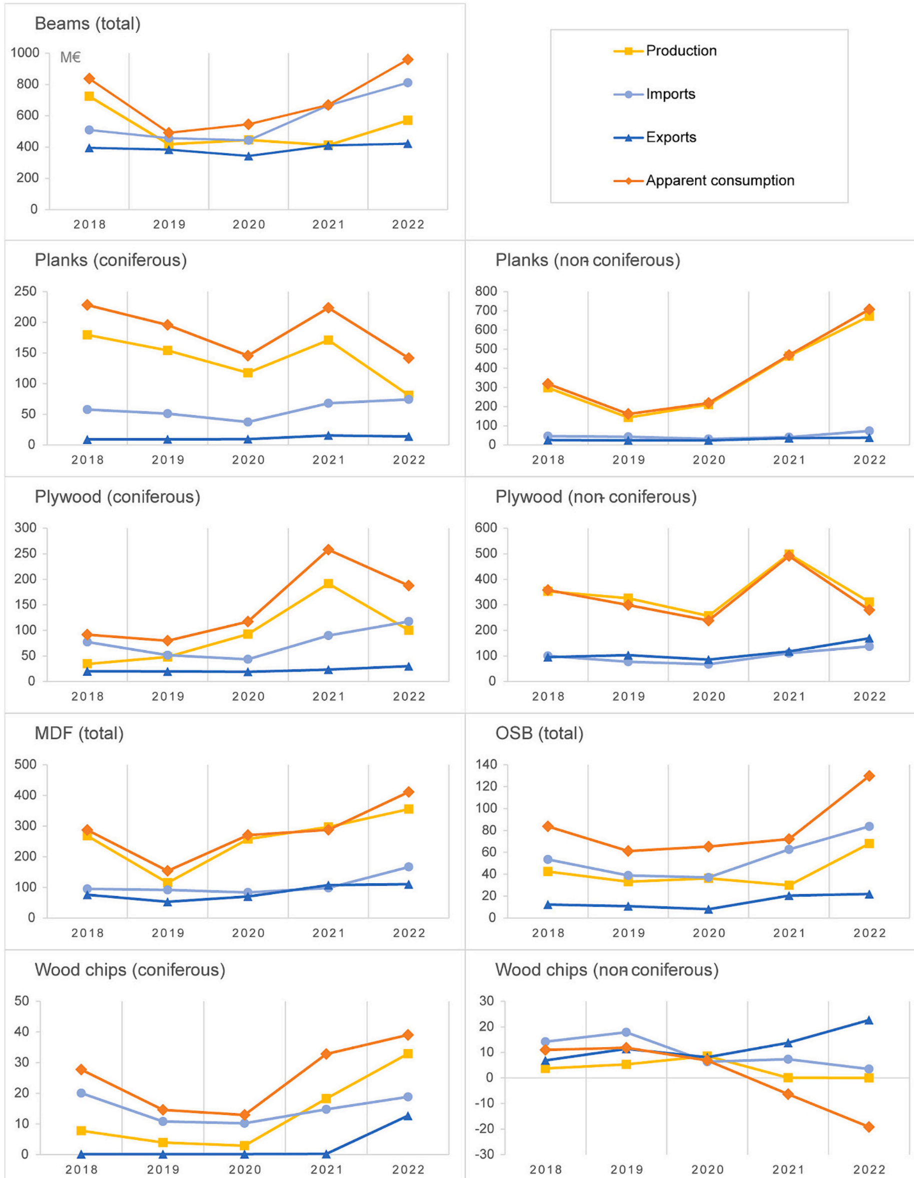

Fig. 6. Italian apparent consumption evolution of the studied wood commodities between 2018 and 2022. Values presented in millions of euros. Source: author's estimation with data retrieved from ISTAT and UN Comtrade databases.]

consumption of wood products, reveals a trend of market contraction in Europe and relative stability in Italy. This trend aligns with the observations in the UNECE and FAO Forest Products Annual Market Review 2022–2023 (UNECE/FAO, 2023), which highlights various factors potentially impacting the forest products market, such as trends in the construction market and deceleration in economic growth. Overall, we believe these findings may provide valuable insights that could contribute to the understanding of the current trends in bioeconomy concerning wood products. However, further confirmation requires a broader analysis that takes into account the numerous macroeconomic transformations occurring in these turbulent years.

CRediT authorship contribution statement

Nuria Goldaraz-Salamero: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jorge Sierra-Perez:** Writing – review & editing, Supervision, Methodology. **Francesco Negro:** Writing – review & editing, Supervision, Data curation, Conceptualization. **Roberto Zanuttini:** Writing – review & editing, Validation. **Simone Blanc:** Writing – review & editing, Validation, Supervision, Methodology, Data curation, Conceptualization. **Filippo Brun:** Writing – review & editing, Validation, Supervision.

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.175601.

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