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REVIEW

Life cycle assessment and circular practices in the woodworking sector: a systematic review

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Abstract

To shift toward a bio-based and circular economy, wood is seen as a key component. To assess the environmental impact of wood utilization, life cycle assessment (LCA) is used. However, current LCAs lack comparability. To be comparable, LCAs must be reproducible, transparent, and follow the same approach. Hence, the goal of the study is to identify the level of harmonization among state-of-the-art LCA applications within the woodworking sector via a comprehensive systematic literature review. The results show that LCA has been applied to various products and processes in the woodworking sector and highlight the predominance of the construction sector. Examining the different LCA phases, different approaches and policies are identified. Recommendations are presented on how LCAs for the woodworking sector can be streamlined. This involves general recommendations for LCA practitioners and policymakers to have at least a cradle-to-grave approach, a standardization of the background and the technical backbone of the foreground system, a harmonized impact assessment method, and performing a sensitivity analysis for the interpretation of the results. For woodworking specifically, temporal, and spatial considerations, accounting for timing of emissions and land use (change), should be included as well as proper End-of-Life considerations via a cascading approach. The increased adoption of wood as a clean technology offers a promising environmental performance; particularly, if forests are sustainably managed, wood modifications are non-fossil and non-toxic, and circular strategies are incorporated. To fully realize its potential, it is essential to standardize LCA methodologies which can set an example to support regulatory policies.

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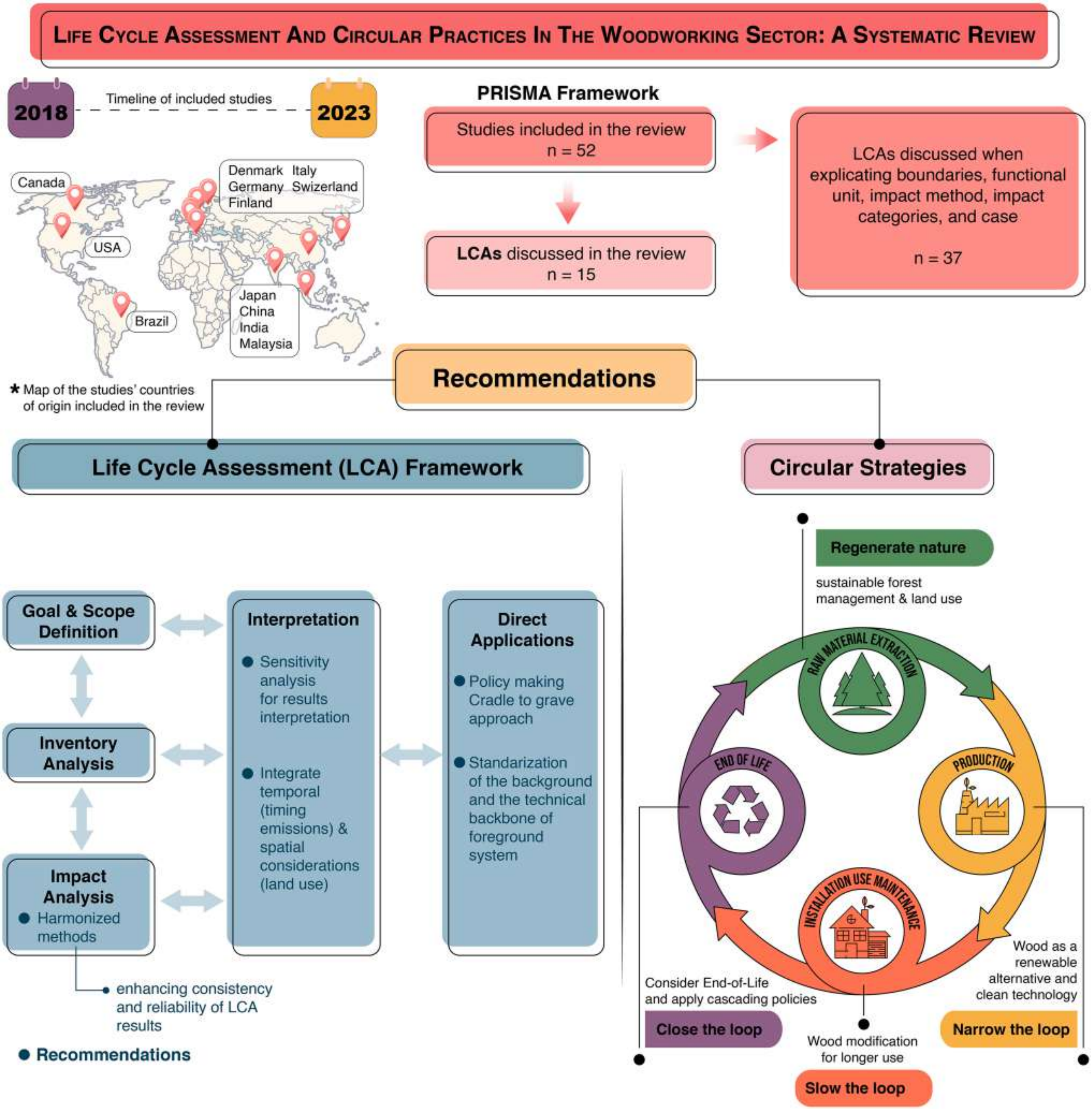
Graphical abstract



Keywords Life cycle assessment · Woodworking sector · Forest-based products · Timber · Green economy · Circular strategies

Abbreviations

ALCA	Attributional life cycle assessment
CE	Circular economy
CLCA	Consequential life cycle assessment
CLT	Cross-laminated timber
EFO-LCI	European life cycle inventory of forestry operations
EoL	End-of-life
EPD	Environmental product declaration
ETEA	Environmental techno-economic assessment

EU	European union
FAO	Food & agriculture organisation
FU	Functional unit
GDP	Gross domestic product
Glulam	Glued-laminated timber
LCA	Life cycle assessment
LCIA	Life cycle impact assessment
LCC	Life cycle cost
LCSA	Life cycle sustainability assessment
MCDM	Multi-criteria decision-making methodology
MFA	Material flow analysis
PCR	Product category rules
PEF	Product environmental footprint
SA	Sensitivity analysis
SLCA	Social life cycle assessment
SMEs	Small and medium-sized enterprises
TEA	Techno-economic assessment
TSA	Techno-sustainability assessment

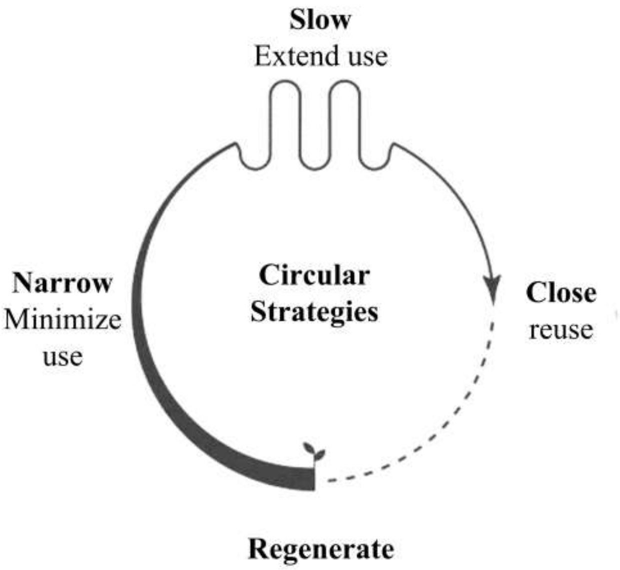


Fig. 1 Circular strategies based on Bocken et al. (2016)

Introduction

The European Commission incentivizes a shift toward a bio-based (European Commission 2018) and circular economy (European Commission 2020) to tackle the current environmental challenges. Their Circular Economy (CE) Action Plan defines the CE as an economy where the value of products, materials and resources is maintained for as long as possible, and the generation of waste is minimized. According to literature, the Circular Economy aims to minimize resource input, waste, emissions, and energy leakage by adopting four strategies to move from a linear to a circular economy: slowing, closing, and narrowing material and energy loops and regenerate nature (Geissdoerfer et al. 2017). Firstly, to narrow and reduce material or energy flows; secondly, to slow down and use products and components for longer; thirdly, to close loops and use products, components, and material again; and fourthly, to use non-toxic materials, renewable energy, and regenerate natural ecosystems as seen in Fig. 1 (Bocken et al. 2016; Konietzko et al. 2020). Long-lasting design, maintenance, repair, reuse, and recycling are key components. The R-strategies or 10R approach categorize these strategies into short, medium, and long loops, reflecting their sustainability and material efficiency (Potting et al. 2017). Short loops prioritize smarter product use (Refuse, Rethink, Reduce), medium loops focus on life extension (Reuse, Repair, Refurbish, Remanufacture, Re-purpose), and long loops emphasize creative material application (Recycle, Recover).

The bioeconomy, on the other hand, means using biological renewable resources from sea and land (EU 2018). As an ‘umbrella’ concept for the circular and bioeconomy, the term green economy is used (D'Amato et al. 2017). This encompasses an ecosystem-driven economy that aims to replace the vast array of non-renewable products now in use by emphasizing the utilization of renewable natural capital and avoiding waste. In this context, the use of wood as a renewable and sustainable resource has gained increasing attention in recent years not only due to its potential to reduce greenhouse gas emissions but also to promote the green economy (Jarre et al. 2020). Wood is an important renewable resource for this future green economy and has a long history of usage for various purposes, including the manufacturing of furniture, paper, construction, and other woodworking products (European Commission 2015). The woodworking industry comprises the production of sawn wood, wooden construction materials, wood-based panels, and other products that are derived from wood. These activities utilize a variety of processes, including logging, sawmilling, and woodworking, to transform raw materials into high-value end products (European Commission 2015). The woodworking sector is of uttermost importance as approximately 70% of the wood in the EU is used as mass timber, mainly in construction and to a minor degree in the furnishing industry. As such, it helps to keep wealth generation and employment in rural areas. In EU alone, the woodworking industries add significantly to GDP with a turnover of €122 billion and an added value of €31.2 billion while employing a little over 1 million people, working in 184 thousand companies from which most are small or medium-sized enterprises (SMEs) (European Commission 2015). It is at the forefront of creating a low carbon economy because of its renewability and carbon storing capabilities. Especially, in the building industry, it has recently gained prominence as a more environmental-friendly substitute for concrete and steel (Goldhahn et al. 2021). One of the largest potentials to mitigate climate change is found in carbon-sequestering in forests or wood products and particularly the combination of carbon storage and displacement from the use of wooden materials in the construction sector (Oliver et al. 2014).

Currently, there is not an equal playing field for bio-based products compared with fossil products, for which environmental performance requirements are less stringent (Sahoo et al.2019). To assess the EP of products and technologies within the woodworking sector as well as to compare alternatives such as plastic, concrete, or steel, life cycle assessment (LCA) is a widely used method. LCA evaluates the environmental impacts of products and processes throughout their life cycles, from raw material exploitation to End-of-Life (EoL) and disposal stage. Many studies use LCA because of its thorough structure (Guinee et al. 2011) as defined in the ISO standards 14040 and 14044 (ISO 2022). LCA facilitates a holistic environmental assessment by considering multiple impact categories, such as global warming potential, allowing designers, policymakers, and decision-makers to compare the trade-offs associated with different alternatives. However, the exact implementation of these standards severely depends on the goal and scope of the LCA. Therefore, it is important to review and analyze the current state of LCA practices in the woodworking sector in a systematic way. LCA is found most commonly used research methodology used for evaluating environmental impacts of wood-based products, especially considering cascade utilization (Thonemann and Schumann 2018).

D'Amato et al. (2020) conducted a systematic literature review of LCAs for forest-based bioeconomy products and processes comprising articles between the years of 2016 and 2018 (D'Amato et al. 2020). Nonetheless, it assesses low-value bio-based products (such as wood residuals used for paper, biofuel, and energy). The LCA of biofuels (Mirkouei et al. 2017) and bioenergy (Patel et al. 2016) have been extensively studied in review publications. Hence, these lower-value products, along with paper goods, pulpwood, and biochar, are excluded from this study. Sahoo et al. wrote a review on the EP of manufacturing forest-based products with a focus on higher-value products such mass timber and nanomaterials in the period between 2005 and 2018 (Sahoo et al.2019). Nevertheless, in their study only attributional LCAs are considered, the focus is on the United States, and not all LCA phases are elaborated: scope, life cycle inventory, life cycle impact assessment, and interpretation as seen in Fig. 2.

In summary, the available literature reviews on LCA for the woodworking sector are (i) outdated as the most recent LCA study covered in these dates from 2018, (ii) are focused on specific types of products or spatiotemporal context (e.g., limited to United states), (iii) are mainly limited to attributional LCAs and (iv) do not provide a clear and thorough description of all steps in an LCA.

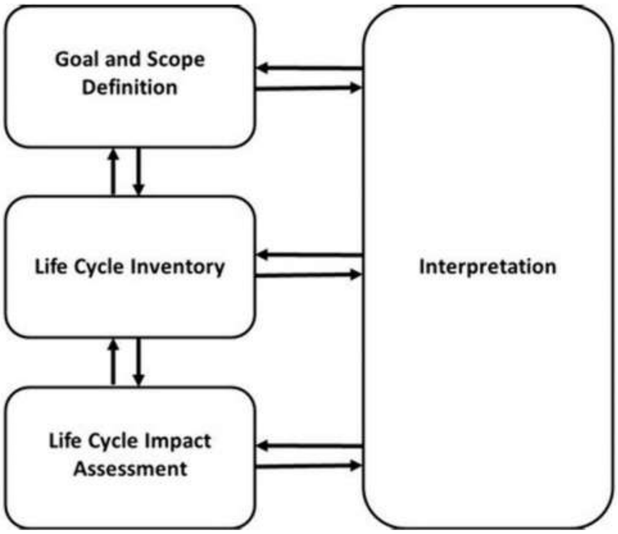


Fig. 2 LCA steps based on ISO (2022)

This systematic literature review aims to overcome the present literature gaps on LCA for the woodworking sector by (i) providing an updated (studies between 2018 and 2023) and more holistic perspective on LCA practices for applications in the woodworking sector with concrete guidelines for each LCA step, (ii) suggesting actions to reduce the environmental impact of the fast-paced woodworking sector, (iii) including consequential LCA studies and (iv) providing a framing to circular economy strategies.

Methods

This systematic literature review follows a rigorous and transparent methodology to identify, select, and analyze relevant articles on LCA practices in the woodworking sector. Therefore, the PRISMA guidelines are followed as depicted in Fig. 3 (PRISMA 2020). It provides a holistic perspective including different LCA approaches, additional perspectives onto LCA, and EP updates within a global geographical scope, with a focus on EU policy. Following studies covering a period up to 2018 (D'Amato et al. 2020; Sahoo et al. 2019), the search strategy involved the electronic database 'Web of Science' from January 2018 to January 2023. Relevant keywords "life cycle assessment", "LCA" and "life cycle analysis" as well as "wood", "forest-based", "lumber" and "timber" are used. The search resulted in 2314 articles which were further screened. LCA studies conducted in industry or by private organizations which are not published in the open academic literature are out of scope of this

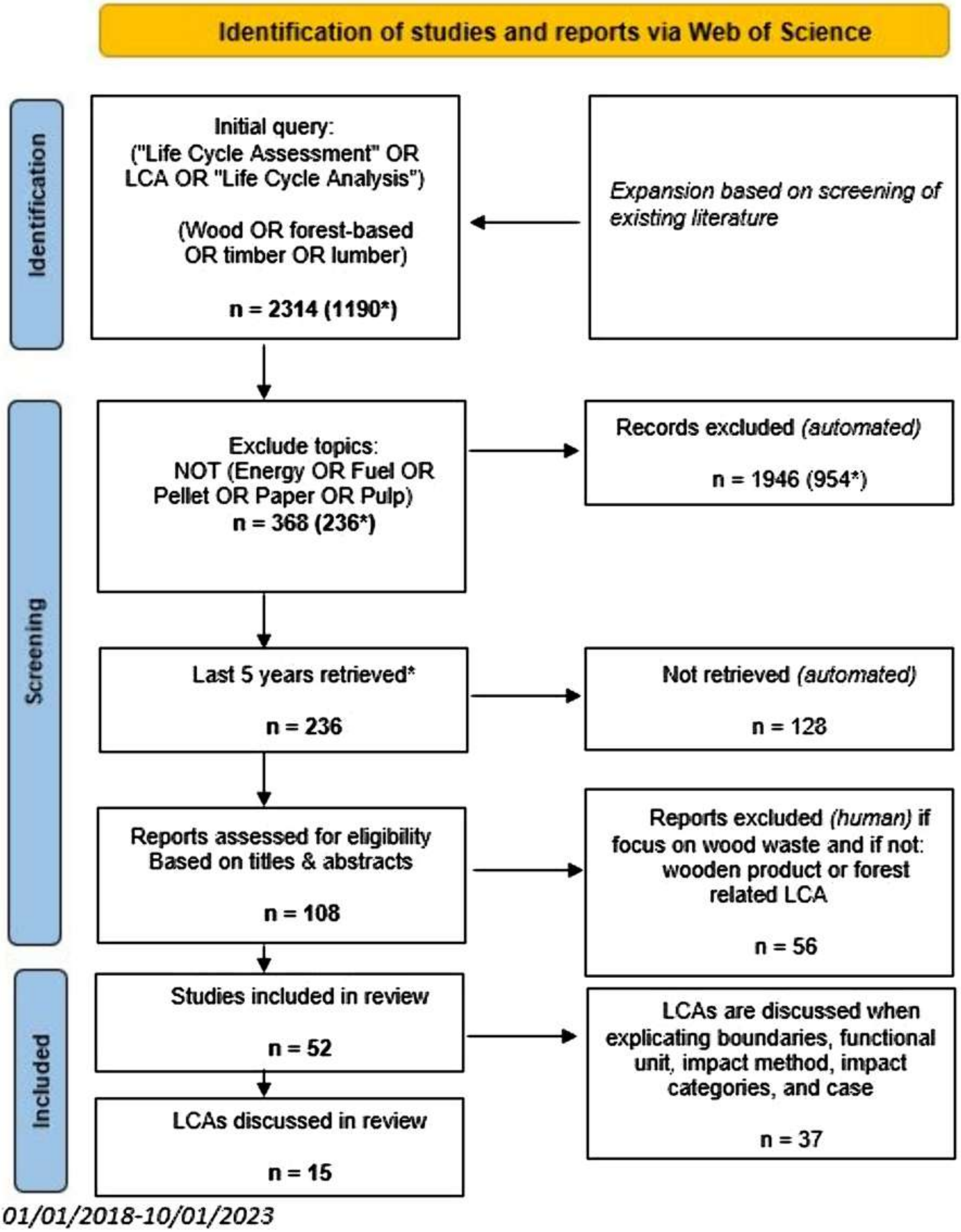


Fig. 3 Process of sample selection, based on PRISMA (2020)

review. The systematic review process commenced with the establishment of stringent exclusion criteria to ensure the focus and relevance of the study. The exclusion criteria were articles that did not report primary LCA studies or were not relevant to the scope of the review, including wood waste and other uses of wood for energy or paper purposes. Specifically, records not pertinent to predefined topics such as energy and fuel; wood pellets, and pulp and paper industry were excluded, resulting in the automation inclusion of 368 records, of which 236 were from the specified timeframe of 2018–2023. Subsequently, an initial screening of reports based on titles and abstracts was performed by the authors, resulting in the identification of 108 reports deemed eligible for further evaluation. Further refinement of the selection process ensued, during which 128 reports were excluded. These exclusions primarily stemmed from reports focusing on wood waste or lacking relevance to wooden products or forest related LCAs. Ultimately, 52 studies were deemed suitable for inclusion in the systematic review. Of these, 15 studies explicitly addressed LCAs, providing detailed discussions on methodological aspects such as boundaries, functional units, impact methods, impact categories, and specific case studies. Within the cohort of included studies, 37 studies provided comprehensive discussions on LCAs within woodworking, while the remaining 15 studies constituted review articles offering overarching insights into LCAs within the context of wood and woodworking products (Table 1).

These 52 articles were selected for analysis based on their relevance, methodological approach, and key findings as can be seen in Table 2 in the Literature Set section. All results were compatible with each outcome domain in each study for the indicated measures and time points. The articles were analyzed using the systematic PRISMA framework that included the following categories: study objective, product/process scope, methodological approach, data quality, results and conclusions, and recommendations (PRISMA 2020). There is an extensive variability in the scope, approaches, and indicators used by the examined research. Therefore, the focus is firstly on the different LCA phases. LCAs are analyzed and discussed when explicating boundaries, functional unit, impact method, impact categories, and case study. This resulted in a subset of 15 studies as can be seen in LCA Case studies in the woodworking sector explicating system boundaries, functional unit (FU), impact method, and impact categories with SA: Sensitivity analysis, A: Attributional LCA and C: consequential LCA. Table 1.

In the results section, firstly, the distinct phases of the LCA will be discussed as defined in ISO standards 14040:2006, 14044:2006, and ISO 14074:2022 (ISO 2022). Next, different LCA methods will be discussed. Subsequently, case studies and good practices will be categorized according to the circular strategies as described by Bocken et al. as seen in Fig. 1 (Bocken et al. 2016). Lastly,

Table 1 LCA Case studies in the woodworking sector explicating system boundaries, functional unit (FU), impact method, and impact categories with SA: sensitivity analysis, A: attributional LCA and C: consequential LCA

Scope	Case	FU	System boundaries	Impact method	SA	LCA	References
Flooring	Ceramic, wooden, or concrete tile, and laminate	1 m^2	Cradle-to-grave	ReCiPe	Yes	A	Balasbaneh et al. (2021)
Residential building	Mass timber, concrete	1 m^2	Cradle-to-gate	Traci 2.1		A	Chen et al. (2022)
Timber sourcing	Different regions	1 $	Cradle-to-gate	ReCiPe		A	Roberts et al. (2022)
Facades	Coated, thermally modified	1 m^2	Cradle-to-gate	Impact 2002+		A	Buryova and Sedlak (2021)
Building	CLT, concrete, timber, renovation	1 m^2	Cradle-to-cradle	ReCiPe	Yes	A	Ryberg et al. (2021)
Pallets	Wooden, plastic, wood-polymer composite	1000 trips	Cradle-to-grave	CML	Yes	A&C	Khan et al. (2021)
Building components	Wood, concrete, steel, gravel, aluminum, gypsum, brick	10,341.2 m^2	Cradle-to-grave	ReCiPe, Impact 2002 +	Yes	A&C	Fauzi et al. (2021)
Ceiling elements	Wood, concrete	30.6 m^2	Cradle-to-gate	N/A		A	Bezama et al. (2021)
Construction framing	Masonry, steel, wood	1 m^2	Cradle-to-cradle	N/A		A	Kayaçetin et al. (2023)
Window, column, roof felt	Timber, concrete	Various	Cradle-to-grave	CML	Yes	A	Eberhardt et al. (2020)
Wood adhesives	Bio-based, fossil-based	1 kg	Cradle-to-gate	ReCiPe	Yes	A	Arias et al. (2020)
Structures	Wood, glulam	1 m^3	Cradle-to-gate, cradle-to-grave	EPD	Yes	A	Dias et al. (2020)
Building	Massive timber, masonry	1 m^2	Cradle-to-gate	ReCiPe		A	Pittau et al. (2019)
Wood-based boards	Different coatings	7 m^2, 1 m^2	cradle-to-gate, cradle-to-grave	100a, CML USEtox,	Yes	A	Nakano et al. (2018)
Structural timber	Spruce timber	1 m^3	Cradle-to-grave	N/A	Yes	C	De Rosa et al. (2018)

Table 2 Literature set

	Article title	References
1	Integrated decision support for embodied impact assessment of circular and bio-based building components	Kayaçetin et al. (2023)
2	Dynamic LCA of the increased use of wood in buildings and its consequences: integration of CO2 sequestration and material substitutions	Cordier et al. (2022)
3	The environmental and social impacts of modified wood production: effect of timber sourcing	Roberts et al. (2022)
4	Life cycle assessment of construction materials and its environmental impacts for sustainable development	Desai and Bheemrao (2022)
5	Review of the use of solid wood as an external cladding material in the built environment	Hill et al. (2022)
6	Life cycle assessment as a guide for designing circular business models in the wood panel industry: a critical review	Araujo et al. (2022)
7	Comparative life cycle assessment of mass timber and concrete residential buildings: a case study in China	Chen et al. (2022)
8	CATWOOD—reverse logistics process model for quantitative assessment of recovered wood management	Vimpolsek and Lisec (2022)
9	Life cycle assessment of coated and thermally modified wood facades	Buryova and Sedlak (2021)
10	Effects on global forests and wood product markets of increased demand for mass timber	Nepal et al. (2021)
11	Sustainability in wood materials science: an opinion about current material development techniques and the end of lifetime perspectives	Goldhahn et al. (2021)
12	Eco-sustainable wood waste panels for building applications: influence of different species and assembling techniques on thermal, acoustic, and environmental performance	Merli et al. (2021)
13	Comparative life cycle assessment of four buildings in Greenland	Ryberg et al. (2021)
14	Environmental impacts of wooden, plastic, and wood-polymer composite pallet: a life cycle assessment approach	Khan et al. 2021)
15	Embodied carbon assessment using a dynamic climate model: case-study comparison of a concrete, steel and timber building structure	Hawkins et al. (2021)
16	Life cycle assessment and life cycle costing of multistorey building: attributional and consequential perspectives	Fauzi et al. (2021)
17	Integrating Regionalized Socioeconomic considerations onto life cycle assessment for evaluating bioeconomy value chains: a case study on hybrid wood-concrete ceiling elements	Bezama et al. (2021)
18	Whole-life embodied carbon in multistorey buildings: Steel, concrete and timber structures	Hart et al. (2021b)
19	Wood product carbon substitution benefits: a critical review of assumptions	Howard et al. (2021)
20	Applying three pillar indicator assessments on alternative floor systems: life cycle study	Balasbaneh et al. (2021)
21	Carbon life cycle assessment on California-specific wood products industries: do data backup general default values for wood harvest and processing?	Buchholz et al. (2021)
22	Temporally-differentiated biogenic carbon accounting of wood building product life cycles	Head et al. (2021)
23	Estimating dynamic climate change effects of material use in buildings-Timing, uncertainty, and emission sources	Resch et al. (2021)
24	Accounting for biogenic carbon and end-of-life allocation in life cycle assessment of multi-output wood cascade systems	Garcia et al. (2020)
25	Development of a life cycle assessment allocation approach for circular economy in the built environment	Eberhardt et al. (2020)
26	Cradle-to-gate life cycle assessment of bio-adhesives for the wood panel industry. A comparison with petrochemical alternatives	Arias et al. (2020)
27	Comparison of the environmental and structural performance of solid and glued-laminated timber products based on EPDs	Dias et al. (2020)
28	Life cycle inventory for currently harvested birch roundwood	Kuka et al. (2020)
29	Dynamic greenhouse gas life cycle inventory and impact profiles of wood used in Canadian buildings	Head et al. (2020)
30	More timber in construction: unanswered questions and future challenges	Hart and Pomponi (2020)
31	A review of LCA assessments of forest-based bioeconomy products and processes under an ecosystem services perspective	D'Amato et al. (2020)
32	Transforming the bio-based sector toward a circular economy—What can we learn from wood cascading?	Jarre et al. (2020)
33	Life cycle inventory for currently produced pine roundwood	Kuka et al. (2020)
34	Life cycle assessment of forest-based products: a review	Sahoo et al. (2019)
35	Modeling the environmental sustainability of timber structures: a case study	Zubizarreta et al. (2019)
36	Forestry carbon budget models to improve biogenic carbon accounting in life cycle assessment	Head et al. (2021)
37	Circular economy practices on wood panels: a bibliographic analysis	Araujo et al. (2019)
38	Enhancing consistency in consequential life cycle inventory through material flow analysis	Cordier et al. (2019)

Table 2 (continued)

	Article title	References
39	Linking construction timber carbon storage with land use and forestry management practices	Forster et al. (2019)
40	Massive timber building versus conventional masonry building. A comparative life cycle assessment of an Italian case study	Pittau et al. (2019)
41	Forest sector greenhouse gas emissions sensitivity to changes in forest management in Maine (USA)	Gunn and Buchholz (2018)
42	Life cycle inventory analysis of the wood pallet repair process in the united states	Park et al. (2017)
43	Feasibility study of mass-timber cores for the UBC tall wood building	Connolly et al. (2018)
44	Method for assessing the national implications of environmental impacts from timber building—an exemplary study for residential buildings in Germany	Hafner and Rüter (2018)
45	EFO-LCI: a new life cycle inventory database of forestry operations in Europe	Cardellini et al. (2018)
46	Recycling processes and quality of secondary materials: food for thought for waste-management-oriented life cycle assessment studies	Rigamonti et al. (2018)
47	Environmental aspects of material efficiency versus carbon storage in timber buildings	Hafner and Schäfer (2017)
48	Assessing the greenhouse gas effects of harvested wood products manufactured from managed forests in Canada	Chen et al. (2018)
49	Life cycle assessment of wood-based boards produced in Japan and impact of formaldehyde emissions during the use stage	Nakano et al. (2018)
50	Fast-growing bio-based materials as an opportunity for storing carbon in exterior walls	Pittau et al. (2018)
51	How methodological choices affect LCA climate impact results: the case of structural timber	De Rosa et al. (2018)
52	Impacts of the allocation assumption in life cycle assessments of wood-based panels	Taylor et al. (2017)

complementary tools to LCA such as material flow analysis (MFA) are discussed as well as the extension to a more holistic assessment accounting for social and economic indicators.

As LCA studies have differences in their life cycle modeling, four models are mainly considered: cradle-to-gate, gate-to-gate, cradle-to-grave, and cradle-to-cradle. The cradle-to-gate approach evaluates the environmental impact of a product from the point of raw material extraction to the point of manufacture (stage A1–5 in Fig. 4) while gate-to-gate focuses solely on the environmental impact originating from the activities within the boundaries of a facility or company, e.g., from entering the factory to the point where it leaves the factory gate. It does not include the impact of the product's use, disposal, or recycling. The cradle-to-grave approach evaluates the environmental impact of a product

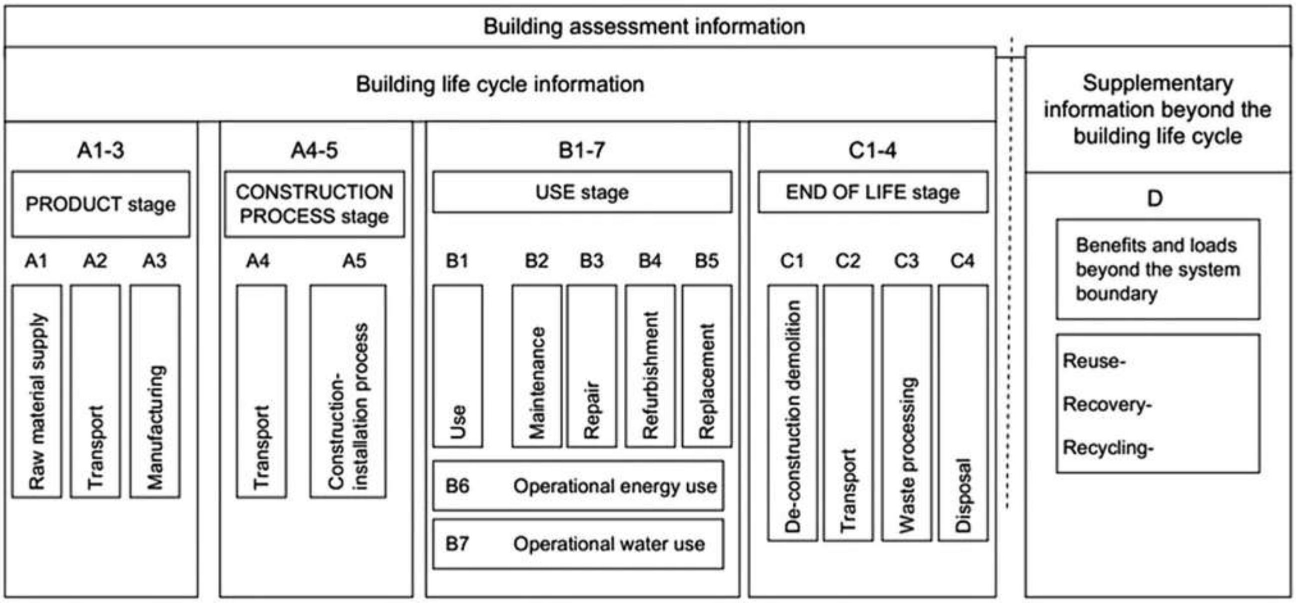


Fig. 4 LCA stages and system boundaries according to EN 15978:2011

from the point of raw material extraction to the point of disposal. It includes the impact of the product's use, as well as its disposal (stage A1–C4 in Fig. 4). Lastly, the cradle-to-cradle approach evaluates the environmental impacts of a product over its entire life cycle and considers the potential for the product to be recycled or repurposed at the end of its useful life including stages A1-D as seen in Fig. 4 (Sonnemann 2011).

Results and discussion

The 52 studies consider 27 different countries and 84 cases as some studies include more than one country. The cases originated mainly from Europe (20 different countries, 57 cases) and from America (3 different countries, 22 cases). European countries with more than five cases each are Denmark, Germany, Italy, Finland, and Switzerland. Also, four Asian countries with five cases were included. Articles are almost evenly distributed between 2018 and 2022 (between 8 and 11 yearly) except for the peak in 2021, counting 15 articles. Also, one article from 2023 was considered which was published at the very beginning of the year.

Phase 1: definition of goal and scope

The first phase defines the scope and goal of the study to set the objectives and system boundaries resulting in the definition of a functional unit and context-related parameters (e.g., related to geographical location and time). The functional unit identifies the product or service being assessed, its functions, and the environmental impacts to be studied (Sonnemann 2011). The assessed products are all examples from the woodworking sector, mainly from the built environment, which are compared to alternatives including steel, concrete, plastics, composites, clay, or ceramics. Examples are the comparison of wooden frameworks to steel and masonry (Kayaçetin et al. 2023) and timber in building versus concrete (Chen et al. 2022) or cross-laminated timber (CLT) (Ryberg et al. 2021). The studied LCA cases can be found in Table 1.

In 73% of cases, the functional unit was measured by surface area, with 82% of these cases expressing it as 1m2. Consequently, 60% of all cases adopted a functional unit of 1m2, indicating its widespread popularity.

Within the study on forest-based bioeconomy products, the methodological approaches used in the LCA studies varied significantly within all the four models considered while some focused on specific life cycle stages (D'Amato et al. 2020). Most commonly for these forest-based bioeconomy products are the cradle-to-gate (48%) and cradle-to-grave (34%) approaches while 8% are gate-to-gate. For this review, it was found that cradle-to-gate is the most predominant approach (46%) closely followed by cradle-to-grave (43%). Cradle-to-cradle was only observed in 11% of the cases while no gate-to-gate cases. Although different wording is used, all studies account for production. As a result, slightly more than half of the studies take construction, use phase, and EoL scenarios into account while 11% goes beyond.

Cradle-to-gate assessments are often used for environmental product declarations (EPDs) which are standardized certifications of an LCA. The development of EPDs, their accompanying product category rules (PCRs), and more recently product environmental footprints (PEFs) marked a first step to make the process of developing LCAs more transparent and allowing comparisons within the same sector (Minkov et al. 2020). PCRs outline the LCA procedures and guarantee that EPDs (or PEFs) are generated that allow for product comparison. The primary PCRs for construction products are detailed in the European Standard EN 15804 (2012+A2:2019 specifically for construction works) (Hill et al. 2022). Nevertheless, the PEF has proven to be ineffective in producing comparable results across different sectors that use different PCRs. Additionally, it has demonstrated compatibility issues with the Environmental Product Declaration (EPD) system and the European Ecolabel (Bach et al. 2018; Durão et al. 2020). The relationship between ISO, EPD and PEF can be seen in Fig. 5.

The current PEF only accounts for cradle-to-gate. Accounting for EoL criteria or beyond brings extra challenges. Nevertheless, the most comprehensive approach is the cradle-to-cradle approach. It considers all stages of the product life cycle, from the forest to EoL as well as the repurposing. Hence, it is advised to aim for the cradle-to-cradle approach, or at least cradle-to-grave, especially as the ISO standards mention to consider EoL treatment (ISO 2022).

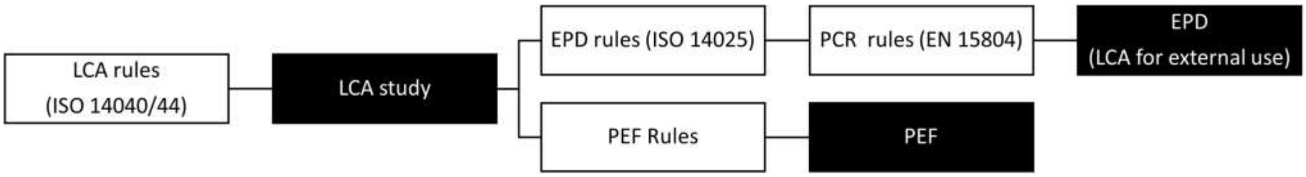


Fig. 5 Relationship between ISO, EPD, and PEF

To address policy fragmentation, a unified methodology for PEF, EPD, and LCAs is crucial for better comparability, reproducibility, and consistency in woodworking assessments and beyond. Expanding PEF beyond cradle-to-gate incentivizes practitioners to adopt comprehensive life cycle perspectives.

In this regard, LCA practitioners and academics play a pivotal role in driving industry standards and shaping regulatory frameworks. By championing best practices and advocating for the adoption of rigorous methodologies, they can set a precedent for sustainable development within the wood industry and beyond. Through collaboration with policymakers, industry stakeholders, and standard-setting bodies, LCA experts can influence and shape the development of robust regulations that promote environmental stewardship.

Phase 2: life cycle inventory (LCI)

The second phase identifies and includes the mass and energy balance of the system. This involves compiling data on the elementary inputs, outputs, and emissions associated with the product or service (Sonnemann 2011). A difference is made between data from the background and foreground system. The first comprises processes and associated data that are not amenable to control or, at the most, can be influenced in an indirect manner by a decision-making entity conducting an LCA. These data and factors can be found in databases such as ecoinvent. On the other hand, the foreground system represents a grouping of processes and data that fall under the purview of the decision-maker responsible for conducting the LCA. These data can be either primary data or simulated, generic or specific.

In 93% of the case studies, the ecoinvent database serves as the primary data source, enhancing reproducibility. However, it is important to note that this reliance on ecoinvent entails an element of estimation, as the specific processes may not always align precisely. Additionally, 20% of the studies supplement their data by utilizing local databases to customize ecoinvent processes, while another 20% incorporate supplementary data sourced from literature. Although all studies transparently disclose their databases, they often lack detailed information regarding specific processes and data, rendering reproducibility challenging. On the one hand, the database offers standardized data, ensuring consistency across studies. However, accessing ecoinvent requires a license, which may be a hurdle for some researchers. Additionally, data quality can vary, potentially affecting the accuracy and reliability of LCA results.

With regards to data for the woodworking sector, depending on the tree species, management practices, and country of production in the European forestry sector, there is a significant variation in the length of rotation, regeneration type, wood product assortment, and machinery used in interventions (Cardellini et al. 2018). These differences affect the life cycle impact of wood production. Therefore, a European Life Cycle Inventory of Forestry Operations (EFO-LCI) was developed which focuses on long-term management and harvesting. In Neumann's study, missing information on forest growth and carbon capture can be found (Neumann et al. 2016). More of these open-source databases and data exchange, including LCI info used in industry, could not only bring more transparency but could also improve the integrity and reproducibility. Ideally, the background data can be standardized as well as the technical backbone of the foreground system and associated data.

Phase 3: life cycle impact assessment (LCIA)

The third phase evaluates the environmental impacts of the inputs and outputs. Here, impact categories chosen in Phase 1 are defined more precisely (Sonnemann 2011). Via characterization factors, the environmental impact per unit of stressor is indicated (e.g., per emission released or per kg of resource extracted). Both midpoint and endpoint approaches are mainstream to derive characterization factors. At the level of human health, ecosystems, and resources, the endpoint approach assesses the damage. The midpoint method, in contrast, evaluates the impact at a point along the cause-and-effect chain between the release of a substance or the use of a resource and the endpoint level (Hauschild et al. 2011). The approaches are complementary as the endpoint method provides additional damage information with a higher degree of interpretation in terms of relevance of the environmental flows while the midpoint approach offers a more reliable evaluation as it has a stronger relation to the environmental flows (Dong and Ng 2014). As seen in Table 1, different methods exist such as the widely accepted ReCiPe, the European standard PEF, and many others such as Eco-Indicator 99, CML, TRACI, and Impact 2002+. As the ISO standard does not specify which LCIA to use, it is recommended to streamline those methods. It can be seen that 40% of the cases apply the ReCiPe method using 18 midpoint indicators and 3 endpoint indicators (Huijbregts 2016). This approach is comprehensive given the complementarity of both mid- and endpoint approaches. The next most used is CML in 20% of the cases. As EU intends to use PEF as standard in the future, it recommended to incorporate elements from ReCiPe such as the inclusion of end points as well as its impact categories. Especially, within the product category of woodworking, end point perspectives must be taken into account to allow for evaluation of the ecosystem quality and resource depletion.

LCA methods are important tools for evaluating impacts throughout product life cycles, but they have limitations when it comes to taking into consideration a variety of concerns connected to ecosystem services (provisioning of natural resources and regulation of biochemical cycles), both at the land use level and along the supply chain (Alejandre et al. 2019; Costanza et al. 2017; Perminova et al. 2016). In a broader review of LCA assessments of forest-based bioeconomy products and processes under an ecosystem services perspective focus on lower-value biomass, D'Amato et al. concluded that almost 90% of the research evaluated climate change, compared to 40% to 60% of studies that evaluated ozone, eutrophication, human toxicity, resource depletion, acidification, and environmental toxicity. While many provisioning and regulating services are covered by the effect categories taken into consideration in the LCA studies that have been evaluated, several ecosystem services, particularly cultural ones, are not (D'Amato et al. 2020). The same trends are seen in the studies considered in this review focusing on higher-value timber where 97% evaluates climate change or global warming. As a result, in the woodworking sector, LCAs are mainly used to identify the impact of global warming. Ozone, eutrophication, human toxicity, resource depletion, acidification, and environmental toxicity are accounted for between 35 and 58% of the cases which are all relevant for woodworking as seen in Fig. 6. Other categories with than a frequency below 30% but above 10% included: abiotic depletion, water consumption, mineral resource scarcity, ozone formation, photochemical oxidation, land use, particulate matter, radiation, and waste. Thoneman et al. (2018) also highlight global warming, eutrophication, and acidification as the primary environmental concerns in their systematic review spanning from 1998 to 2015 (Thonemann and Schumann 2018). However, they suggest integrating resource depletion more frequently, as this was underrepresented. Interestingly, land use was considered in nearly half of the cases. However, the opposite trend is seen with land use only observed in 13% of the reviewed studies. Accounting for land use in wood and woodworking product assessments is vital because it helps evaluate carbon sequestration, biodiversity preservation, soil, and water quality, and promotes sustainable land management practices. In particular wood, harvesting and forest conversion can lead to habitat loss, fragmentation, and species displacement. Deforestation and intensive forestry practices may contribute to soil erosion, nutrient depletion, and water pollution, impacting local ecosystems and communities. By promoting responsible forestry practices, such as reforestation, agroforestry, and ecosystem restoration, land use assessments can support the conservation of natural resources and ecosystem services over the long term. Although LCA is the most widespread method to assess land use, it is ideally combined with a second method, such as Environmental Impact Assessment or MFA, depending on the case study (Perminova et al. 2016).

Next to land use also EoL and production waste, fresh water use for growing trees, and optionally smog from transportation should be accounted for in addition to general observed categories.

Phase 4: interpretation of the results

In the last phase, the interpretation and analysis of the results of the impact assessment are done to draw conclusions on the environmental impacts. These results can explain constraints and offer suggestions in line with the goal and scope that have been established. Therefore, a sensitivity analysis is indispensable (Sonnemann 2011). It is observed that 60% of cases mention a sensitivity analysis. A sensitivity analysis in LCA is crucial for assessing the impact of varying parameters on study outcomes, revealing key drivers of results and quantifying uncertainty. Variability in data sources, modeling assumptions, and methodological choices

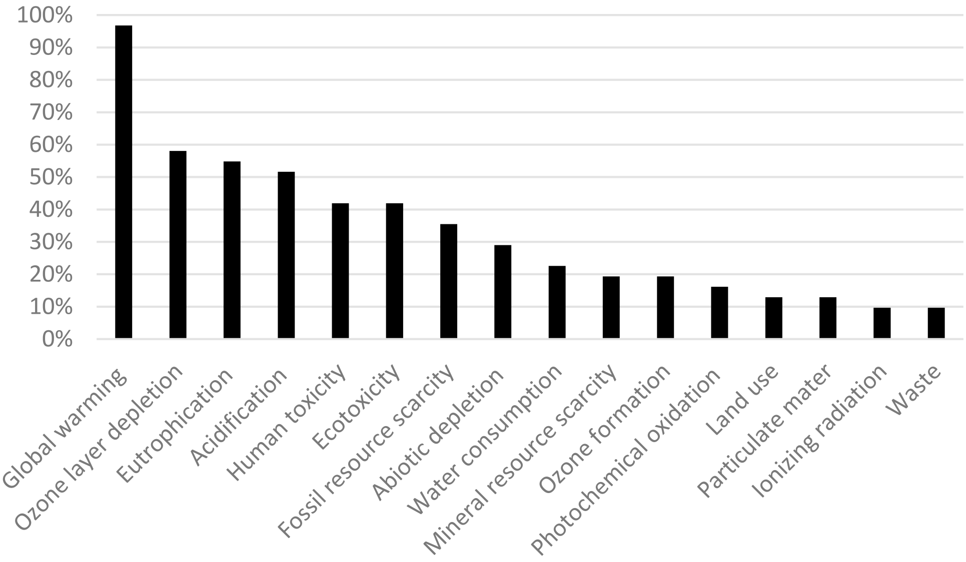


Fig. 6 Frequency of the individual impact categories analyzed in the reviewed studies

contributes to uncertainty, emphasizing the need for rigorous analysis and transparent reporting to ensure the reliability of LCA findings. In all studied LCAs, the focus primarily stems from the technology or product viewpoint, often from the manufacturer's standpoint. However, this narrow perspective may overlook crucial aspects of the entire supply chain and its various stakeholders, leading to potential biases. Therefore, adopting a multistakeholder approach that considers the entire value chain is essential for a comprehensive assessment of environmental impacts and sustainability implications.

The actual results from the studies within this review are discussed separately in the section on life cycle lessons and will be categorized according to the proposed circular strategies.

Attributional versus consequential approaches

Two distinct approaches to life cycle assessment (LCA) are acknowledged: attributional and consequential LCA. Attributional life cycle assessment (ALCA) quantifies a product's share of global environmental impacts, while the consequential approach (CLCA) assesses how production and usage influence global environmental burdens. ALCA typically relies on average data and allocates environmental loads among life cycle stages, whereas CLCA preferably employs marginal data and avoids allocation through system expansion (Sonnemann 2011). The objective of attributional modeling is to analyze specific product aspects, whereas consequential modeling reflects physical and monetary causalities, providing a market perspective. Generally, attributional methods are more prevalent than consequential ones (Fauzi et al. 2021). Only a small fraction of LCAs, estimated less than 5%, employ CLCA (IFP 2020), yet it appears in 16% of woodworking sector analyses in this study. This suggests either growing popularity in this sector or its suitability due to the importance of marginal supply increases. An example of woodworking CLCA involves assessing how changes in land use for tree cultivation in one area affect land use elsewhere, such as indirect land use change. While ALCA is commonly used for specific footprint development, such as Environmental product declarations (EPDs) or Ecolabel criteria, which allow for hot-spot analysis and comparison, considering potential market demand changes is can be essential in other cases.

Fauzi et al. (2021) examined attributional and consequential perspectives in construction, finding that material production's environmental impact is greater in ALCA (86–98%) than in CLCA (46–94%). (Fauzi et al. 2021). Similarly, a study comparing wooden, plastic, and wood-plastic composite pallets found that despite distinct perspectives, both approaches favored the same scenario for environmental performance (Khan et al. 2021). This demonstrates that the consequential and attributional approaches can give a distinct perspective without contradicting one another. Cordier et al. (2022) argued that CLCA could provide more precise information than ALCA, emphasizing a consequential LCA's dynamic nature (Cordier et al. 2022). Nevertheless, dynamic aspects can include more uncertainty. Dynamic modeling in general can yield opposite conclusions compared to static approaches, particularly regarding long-term climate change effects. Furthermore, the contribution of consequential processes to climate impact assessments varies based on study goals, indicators, and time horizons (De Rosa et al. 2018).

Uncertainties inherent in ALCA and CLCA stem from distinct sources, primarily tied to the resolution of multifunctionality issues. In ALCA, uncertainty arises from the choice of allocation criterion, while CLCA introduces uncertainties related to identifying marginal technologies and predicting market-mediated substitutions (Mathiesen et al. 2009). Additional uncertainties in CLCA include assumptions regarding elasticities and future predictions (Ekvall and Weidema 2004). However, recent literature indicates that the analysis of uncertainty in CLCA mirrors that of ALCA, with limited consideration given to addressing these unique and potentially significant uncertainties (Bamber et al. 2020).

Implementing both attributional and consequential LCAs offer a broader range of insights into a product's environmental impacts, facilitating more informed policy and decision-making processes, depending on the goals and scopes of the study.

Life cycle lessons according to circular strategies

Next to how the life cycle environmental impacts are analyzed, the actual results provide a quantification of these as well and indicate their position in the circular economy. The results assess the impact of products in the woodworking sector and propose alternatives, for example to mitigate global warming. Hosseini (2023) assesses circular strategies in construction, focusing on end-of-life considerations for building systems using the 10R approach (Hosseini et al. 2023). Applied to a case study of a residential mass timber building, using life cycle assessment (LCA), it also confirms the effectiveness of CE strategies in reducing environmental impacts (Hosseini et al. 2023). However, in what follows, lessons from the studies will be extrapolated and categorized in line with circular strategies to narrow, slow, close, and regenerate the loop.

Narrow the loop: wood as a renewable alternative and clean technology

Firstly, embracing circular economy principles and narrowing the loop entails streamlining material and energy flows, minimizing waste, reducing material or energy flows, and maximizing efficiency throughout the wood production and woodworking processes. However, the global market for wood products is projected to increase from $631.11 billion in 2021 to $833.00 billion in 2026 with a compound annual growth rate of 7.2% (Research and Markets 2022). Firstly, there is an increased availability and acceptance of engineered timber products, such as CLT and glued-laminated timber (glulam) beams which have a more consistent and predictable performance (Hassegawa et al. 2022; UN 2022). Next, the use of sustainably sourced wood within construction is encouraged in the form of policies, programs and changes in building standards such as the International Building Code while higher prices for non-wood substitutes are seen such as vinyl, cement or aluminum (Botyriute 2022). While this indicates the opposite of narrowing the loop for wood itself, this could mean an overall narrow of resource extraction when wood is replacing other materials with a lower environmental performance. The possibility of utilizing wood products to mitigate climate change has grand expectations, especially as alternative construction material. Several recent studies have shown that reducing carbon emissions associated with the production, transport and installation of building materials by 13–26.5% may be achieved through substitution of wood mass for steel or concrete in buildings (Gu and Bergman 2018; Liang 2020; Pasternack et al. 2022). These predictions rely in large part on long-lasting wood products replacing non-renewable items like steel, concrete, and other building materials. The advantages of this replacement for reducing climate change are frequently discussed and measured as displacement factors (Howard et al. 2021).

In the studied articles, using the wooden alternative does not only emit the least emissions but showed the best overall EP. Only one case comparing a wood-polymer composite to a plastic pallet and a wooden pallet showed a better EP for the wood-polymer composite (Khan et al. 2021). Other studies included a plethora of examples where wood is the overall better choice environmentally. The study of Hawkins et al. (2021) compared concrete, steel, and timber building structures. It was found that, considering sustainable forest management and the release of carbon stored during its lifetime, results in timber having the least adverse effects (Hawkins et al. 2021). A comparative LCA of mass timber and concrete residential buildings in China showed that, compared to concrete architecture, wood buildings have achieved a 25% reduction in global warming potential (Chen et al. 2022). An Italian case study comparing a massive timber building to a conventional masonry building also confirmed the suggestion that the use of wood as a building material instead of conventional masonry materials (clay and concrete) results in a reduction in greenhouse gas emissions of 25% (Pittau et al. 2019). Likewise, a German study for residential buildings showed how increasing timber construction can contribute to achieving climate protection targets (Hafner and Schäfer 2017). This confirms the potential of using more wood in the construction industry, especially given its renewability. Nevertheless, the harvesting and logging of wood can potentially have their own negative environmental impacts (Head et al. 2019). An analysis of the forest management practices in Latvia suggest that logging operations have the largest impact on the EP (Kuka et al. 2020). The manufacturing stage accounts for the biggest environmental impact on the supply chain, whereas forest management and logistics play an important economic role (Sahoo et al. 2019).

Slow the loop: wood modification for longer use

Secondly, it involves extending the lifespan of products and components, encouraging durability, repairability, and reuse to prolong their utility, and reduce consumption. Unsustainable processing and modification methods frequently reduce the sustainability of wood as a sustainable resource. The environmental impact of wood products is determined by the type and source of wood, the production process, and the use and disposal of the products. In general, wooden products mostly rely on fossil-based precursors and produce composites or hybrids that cannot be separated, reused, or recycled (Goldhahn et al. 2021). As such, the woodworking industry is the world's largest user of adhesives, with 70% of the world's volume of adhesives used in the woodworking industry, and around 80% of wood-based products require some form of bonding (Sandberg 2016). Modification can significantly improve the lifetime of wood products although this does not necessarily have to be via (fossil-based) chemicals. For example, for the façades of buildings, the thermally modified façade without any surface coating had the least negative environmental effects. It was demonstrated that the coatings utilized, the surface care techniques used, and the frequency of their application all significantly influenced the environmental impact of the wooden façades (Buryova and Sedlak 2021). On the other hand, Arias et al. showed that the soy-based and tannin-based bio-adhesive had an overall better profile than fossil resins (Arias et al. 2020). A case study demonstrated that due to the reduced environmental impact from reuse and recycling in the EoL scenarios, bio-based product design has an improved EP (Kayaçetin et al. 2023). The discovery and commercialization of wood preservation technologies that change wood at the molecular level to exclude moisture has resulted in long-lasting wood products that are superior to biocide-treated wood in some ways and more ecologically friendly than tropical hardwoods from native forests (Evans et al. 2022). In general, Goldhahn et al. plead for wood modifications that are non-toxic and not fossil-based to allow for EoL strategies with a better

EP (Goldhahn et al. 2021). With this eco-design in mind, products can be created that blend in a circular bioeconomy.

Close the loop: considering EoL and applying cascading policies

Thirdly, it focuses on closing loops by promoting recycling, remanufacturing, and downcycling or upcycling practices. This ensures that wood and woodworking materials are reintegrated into the production cycle rather than discarded, allowing for the reuse of products, components, and materials while choosing the appropriate strategy to minimize transformations and environmental impacts. Monsù Scolaro and De Medici (2021) put this into practice with their methodology to reduce the environmental impacts within the refurbishment and rehabilitation design process for buildings based on CE principles and down or upcycling strategies (Monsù Scolaro and De Medici 2021).

Although LCAs practitioners support the idea that using timber results in a building with lower embodied carbon, a detailed consideration of the EoL scenarios is required (Hart and Pomponi 2020). Even though upfront emissions (from conception to practical completion) account for most of the embodied carbon emissions, post-construction emissions are still significant, particularly for wood, where 36% of emissions typically occur (Hart et al. 2021a). Although timber has an advantage in this comparison, careful consideration of efficient design and procurement is indispensable. A case study of a single-family house found that an increased EP up to 24% for products that were designed for disassembly showing that not only the material but also the design matters (Kayaçetin et al. 2023). However, in practice, most LCAs are conducted ex-post which might mislead policy and decision-makers (Ott and Ebert 2019). Using an ex-ante LCA is recommended to allow for better EP from the design phase.

To maximize the potential of wood and mitigate the climate change, a cascading EoL approach is suggested as a potential solution (Goldhahn et al. 2021). Cascading refers to a circular resource-efficient use (Jarre et al. 2020) and is already promoted on a policy level by the EU in their "Guidance on cascading use of biomass" (European Commission 2019). Some of these practices are already implemented, although it is advised to take these practises already in the design phase into account. An analysis by Jarre et al. (2020) demonstrated that the foundation for reuse and recycling is laid by the physical characteristics of wood products, such as particle size or the presence of chemicals. The most crucial element in this regard is thus the product design (Jarre et al. 2020).

A study by Vimpolsek et al. (2022) indicated that logistics scenarios for reuse are more environmentally friendly than those for recycling or energy recovery, but also more expensive. This is primarily due to the significant amount of manual labor currently required and the technology used in sorting and recovery processes (Vimpolsek and Lisec 2022).

Regenerate nature: sustainable forest management and land use

Fourthly, it emphasizes regeneration by prioritizing the use of non-toxic materials, adopting renewable energy sources in manufacturing processes, and fostering the restoration of natural ecosystems impacted by wood extraction or production activities. By adhering to these principles, the wood industry cannot only minimize its environmental footprint but also foster resilience, innovation, and sustainable growth. When forests are managed sustainably, natural forest regeneration and growth are assumed to replace most of the projected depletion in aggregate forest stock. This suggests small impacts on forest stock at national, regional, and global levels (Nepal et al. 2021). Nepal et al. examined the consequences of differing mass timber demand scenarios up to the year of 2060. According to the findings, the increase in mass timber demand is expected have to an increase in prices for timber products between 2 and 23%. The projected increases in timber prices are expected to increase the economic value of forestland and, as a result, provide a financial incentive to prevent the conversion of forestland (Nepal et al. 2021). A UK study even showed that intensification and expansion of forestry into marginal agricultural land to supply timber for the built environment would have considerable environmental benefits, particularly in terms of reducing GHG emissions and depleting fossil resources (Forster et al. 2019).

While wood can be a better alternative in construction combatting global warming, this does not necessarily mean that it is carbon neutral. Although temporary carbon storage has been acknowledged by standards as a crucial factor to consider in LCAs for wood products, there is still no agreement on a method for its accounting (Head et al. 2021). Garcia et al. (2020) investigated six different carbon footprint methods with different time-related assumptions. The outcome was discovered to be remarkably responsive to the approach employed for measuring the timing of CO_2 absorption in the forest, as opposed to the technique utilized. To effectively choose a method for forest modeling, it is imperative to establish specific parameters, including temporal boundaries and rotation periods (Garcia et al. 2020).

Another study calculated the timing for carbon and ecosystem neutrality for many Canada's forests and commercial tree species. Biogenic carbon profiles were created enabling the modeling of dynamic cradle-to-grave LCAs of wood products. Each species' average time to carbon and ecosystem cost neutrality varied from 16 to 60 years (Head et al. 2019). As such, ecosystem carbon cost per cubic meter of wood harvested can be estimated by knowing the length of time since forest management began on a specific forest landscape. More of these open-source databases, like on the EP of diverse types of wood products, could give a better perspective on which species to consider.

Limitations of LCA in woodworking: toward a holistic sustainability assessment

While LCA is a globally recognized method to perform an impact analysis over the entire life cycle of a product, it only focuses on the environmental aspects. With regards to the circular economy, techniques such as material flow analysis in combination with LCA can be used, for example to model changes in the construction market (Cordier et al. 2019). Additionally, circular tools can support in measuring the potential for reusing and recycling materials (Kayaçetin et al. 2023). For instance, Araujo et al. (2019) showed that the wood panel industry is already using circular economy practices for waste management and shows opportunities from the extraction of raw materials to the EoL disposal (Araujo et al. 2019). Within the same industry, it also suggested that LCA could guide the design and implementation of circular business models toward an improved EP (Araujo et al. 2022) which is also shown in the section on life cycle lessons.

Classically, also economic, and social aspects should be taken into account for a holistic sustainability assessment. Different additional tools are proposed to be integrated with the LCA approach to allow for social or economic elements to add a distinct perspective. When social criteria are considered, this is also known as social LCA (SLCA). Two examples of SCLA are CATWOOD (cascade treatment of wood) incorporating LCA and social life cycle costing (Vimpolsek and Lisec 2022) or the regional specific contextualized social LCA RESPONSA (Bezama et al. 2021). Roberts et al. studied the environmental and social effects of a modified softwood in different regions. The study showed that each region scored poorly in different social aspects making it difficult to provide recommendations without introducing subjective judgments (Roberts et al. 2022).

A frequently used tool to consider economic aspects is Life Cycle Costing (LCC). For example, Fauzi et al. (2021) also investigated which stage did not only impact the environment most but also the economic situation (Fauzi et al. 2021). To combine best of both worlds, Thomassen et al. elaborated a techno-economic assessment (TEA) with LCA concepts which led to and environmental techno-economic assessment (ETEA) (Thomassen et al. 2018).

A life cycle sustainability assessment (LCSA) approach that addresses all three sustainability characteristics in a single evaluation and facilitates decision-making was proposed by the Life Cycle Initiative hosted by the United Nations (Valdivia et al. 2021). Luthin et al. (2023) go even one step further and add a circularity assessment as an additional dimension to LCSA resulting in a C-LCSA including extra material, product, and longevity circularity indicators (Luthin et al. 2023). The LCSA strategy has been used in a number of industries, including bio-based and circular economies as indicated in a review including more than 100 LCSA studies (Fauzi et al. 2019). This review revealed that facilitating stakeholder involvement continues to be difficult and generally sustainability dimensions are still not well harmonized so more technical and practical advice on holistic methodologies is needed. To address this Van Schoubroeck et al. (2021) developed a Techno Sustainability Assessment (TSA) integrating technological, economic, social, and environmental aspect (Van Schoubroeck et al. 2021). However, this method was developed for biochemicals and should be elaborated further to explore other sectors such as woodworking.

Eventually, practitioners should be able to make well-rounded, balanced judgments on the technology's complete sustainability. To evaluate multiple conflicting, multidimensional, and incommensurable criteria in LCA, SLCA, LCC, or LCSA results, a multi-criteria decision-making method (MCDM) can be used (Macharis et al. 2016). As a matter of fact, MCDM is already regarded as a type of integrated sustainability evaluation (Chun Jun 2009). For example, Balasbaneh et al. (2021) evaluated the diverse options coming from the LCA, LCC, and SLCA using MCDM techniques to choose the best flooring option: ceramic tile, laminate, concrete, or wood (Balasbaneh et al. 2021). Wood flooring had the lowest environmental impact overall. According to their LCC results, concrete flooring was the least expensive option, costing 30% less than the second-best choice (wood flooring). SLCA, on the other hand, showed that the laminated option had the least detrimental social impacts. Considering the COPRAS MCDM approach, wood was the most sustainable floor system overall. Another sector-specific example is a multi-attribute value function-based methodology to address the social and environmental evaluation of timber structures. It is developed to introduce environmental and social indicators in design decisions without taking an excessive amount of time so that decisions can be made during the project phase (Zubizarreta et al. 2019). Additional (SLCA or LCC) or integrated (LCSA or TSA) assessments can also account for social and economic aspects, providing a clear broader perspective whereas MCDM can be used to select the preferred design with regards to the different criteria.

Implications of the results for practice, policy, and future research

Professionals working in the field of LCA and policymakers are targeted with recommendations for future LCAs, suggestions to align LCA methodology, and inspiration for circular strategies. Next, the objective is to create awareness in the woodworking sector on potential improvements. Cases and good practices are extrapolated to the sector-wide context to inspire policymakers to advance the green economy. The envisioned impact is to be able to evaluate and advance the green economy which will help to mitigate climate change.

Limitations of this review

The systematic literature review on Life Cycle Assessment (LCA) and circular practices in the woodworking sector acknowledges several limitations. The reliance on the PRISMA (2020) framework and a single search engine, Web of Science, may restrict the scope of identified literature. Exclusion of LCA studies from industry or private organizations not published in open academic sources may overlook valuable insights. Additionally, the focus on primary LCA studies and relevance to the review's scope may omit secondary analyses. Furthermore, excluding studies on wood waste and other wood uses may limit the review's breadth. These limitations underscore the need for cautious interpretation and suggest avenues for future research.

Conclusion

The aim of this systematic literature review is to provide a more holistic perspective on current LCA and circular practices in the woodworking sector and to suggest actions to improve the EP. Based on the systematic approach of PRISMA, 52 articles were selected between 2018 and 2023 discussing the distinct LCA phases, comparing attributional and consequential perspectives, highlighting life cycle lessons and circular practices, and zooming out to a more holistic sustainability assessment.

Primarily, the streamlining of LCA methodologies is essential. Most assessments are cradle-to-gate (48%) closely followed by cradle-to-grave (43%). 40% use the ReCiPe impact method and 60% mention a sensitivity analysis. As such, current LCAs lack harmonized applications which leads to low comparability. It is recommended to use an extensive impact method approach (e.g., ReCiPe) and to perform a sensitivity analysis for the interpretation of the results. The predominance of climate change within the impact categories is outstanding (97%) whereas other categories are only studied in less than 60% of the cases. There is a remarkable of absence of land use as an impact category which is studied is less than 13% of the cases. Harmonizing the way LCAs are conducted and improve the reproducibility and comparability. Likewise, open-source approaches and data sharing improve the integrity and transparency. This can be achieved through the adoption of a cradle-to-grave approach, ensuring that all stages of a product's life cycle are comprehensively considered. Furthermore, standardization of both the background and technical components of the foreground system, as well as the harmonization of impact assessment methods, will enhance the consistency and reliability of LCA results. Going beyond the mere adherence to regulations, both LCA practitioners and academics possess the potential to lead by example and actively shape future regulations.

Aligning LCAs within the woodworking sector and afterward the bio-based sector, is a first step toward a holistic, unified, and harmonized LCA framework. A consequential approach can give a distinct perspective than an attributional LCA for more informed decision-making on a policy level without contrasting the results. To refine the applicability of LCA in the context of woodworking, temporal and spatial considerations must be integrated. This involves accounting for the timing of emissions and land use changes, as these factors play a critical role in the assessment of wood's environmental performance.

LCA results in the woodworking sector are already promising as wood is mostly suggested as the alternative with the best environmental performance especially when forests are sustainably managed, potential modifications are non-fossil and non-toxic, and a circular cascading EoL is already foreseen in the design phase. The utilization of wood as a clean technology holds immense potential for narrowing, slowing, closing, and regenerating the resource loop, as it represents renewable material that can replace steel, concrete, and plastic across various applications. However, to accurately assess and compare the environmental impacts of wood-based products and processes, it is imperative to address several key considerations within life cycle assessment (LCA) methodologies. The adoption of wood as a clean technology is a promising avenue for reducing the environmental footprint of various industries. To fully harness the potential of wood, it is imperative to refine and standardize LCA methodologies, incorporate temporal and spatial considerations, and prioritize the sustainable management of wood resources. This collective effort cannot only promote a more sustainable future but also serve as a model for shaping and influencing regulatory frameworks.

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Data availability The dataset analyzed during the current study is available in the literature set (Table 2).

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose. The authors declare that there are no conflicts of interests.

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