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LCI METHODOLOGY AND DATABASES

Best practices for comparative LCA of bio-based alternatives to fossil-based products

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Abstract

Purpose Substituting fossil-based products with bio-based alternatives is crucial for a sustainable bioeconomy. Comparative Life Cycle Assessment (LCA) studies can provide valuable guidance on when and how the substitution is environmentally sound. However, careful consideration of technical, regulatory, and economic conditions is needed when performing such LCA studies. The present work aims to identify the best practices for conducting a comparative LCA of bio-based products intended to substitute fossil alternatives in five sectors: construction, packaging, textiles, chemicals, and woodworking.

Methods The study is based on two literature reviews, one focusing on the identification of the key challenges in the substitution, and the other reviewing several comparative LCA studies to assess to what extent those challenges were accounted for in the analysis. The findings are used to derive recommendations for multiple stakeholders, primarily for LCA practitioners.

Results and discussion Our analysis shows that while some types of bio-based products exhibit the same technical characteristics as their fossil-based counterparts, others present technical differences as well as differences in durability, and availability. Moreover, bio-based materials frequently require compensatory measures to achieve the same technical performance, such as exterior coatings in packaging. Overlooking those challenges in the comparative LCA can lead to biased comparisons.

Conclusions A thorough accounting of the specific contextual conditions is needed in LCA studies comparing bio-based products versus fossil-based counterparts. Specific recommendations for best LCA practice are provided, by ISO phase, e.g., a clear functional equivalence specification and ensuring that the system boundaries include all activities needed to compensate for differences in functionality. Further quantitative and qualitative research on how following these recommendations can influence the adoption of bio-based products over fossil counterparts is recommended as well.

Keywords Bio-based materials · Life cycle assessment · Construction · Packaging · Textiles · Chemicals · Woodworking

1 Introduction

Bio-based products hold the potential to improve the environmental performance of many sectors in Europe and globally, bringing several direct and indirect benefits such as reducing dependence on non-renewable resources, mitigating climate change, and strengthening European competitiveness (Zuiderveen et al. 2023; Sevigné-Itoiz et al. 2021). To expand bio-based sectors it is however necessary to substitute current fossil-based products and other incumbent products with their bio-based alternatives. On the one hand, these trends call for a better understanding of the ecological boundaries of such a bioeconomy (European Commission: Directorate-General for Research and Innovation 2018) and of how much it can sustain the shift from fossil to bio-based sources (Talwar and Holden 2022). On the other hand, the trends make it increasingly necessary to assess the environmental sustainability and circularity of bio-based products from a life cycle perspective. Life Cycle Assessment (LCA) studies of bio-based products are increasingly needed to ensure that they perform better than incumbent alternatives.

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Bio-based products are wholly or partly derived from biomass, such as plants or algae (European Committee for Standardization 2014), whereas fossil-based products originate from fossil, non-renewable resources, such as natural gas, coal, or oil. Currently, fossil-based products dominate in several sectors (European Commission 2023). In the construction industry, concrete and cementitious products are primarily used (United Nations Environment Programme 2023). In the textile industry, synthetic polyester is the most used fibre (Textile Exchange 2025). In the chemicals sector, 97% of all chemicals produced in Europe are fossil-based, particularly the platform chemicals (European Commission. Joint Research Centre. 2019). In the woodworking sector, wood is by definition the core material, which is bio-based; however, adhesives, which are essential to bond various materials together, are mostly fossil-based (European Commission. Joint Research Centre. 2019). In contrast, bio-based products cover a larger share in the packaging sector with paper and cardboard accounting for approximately 33% of the market, although the majority is still fossil-based (Statista 2025).

In this context, two main problems arise. Firstly, previous studies suggest that substituting current products with bio-based ones might present several challenges and that such substitution may not be straightforward due to specific differences between the products and the context in which they are applied and used. For example, differences in the technical performance, the regulatory framework, or the user behaviour might complicate such comparisons or make them meaningless. Secondly, LCA studies comparing bio-based against fossil-based products might not take into account these differences and contextual conditions, potentially incurring comparability issues that can affect the reliability of the results.

For example, Rinke Dias De Souza et al. (2024) report that some of the challenges associated with substituting fossil-based products with bio-based alternatives are limited biomass availability and low technology readiness level (TRL) of some bio-based technologies. Bos et al. (2024) investigate the challenges of using bioplastics based on a series of interviews. Some of the main challenges reported by interviewees are the lack of end-of-life infrastructures and regulations on recycling, limited availability of materials, and higher prices compared to fossil-based counterparts. Liu et al. (2025) identify the main challenges to an increased use of bio-based materials derived from agricultural residues. Some of them are the relatively small-scale markets for applications, high manufacturing costs, and the lack of advancements in core technologies. Dams et al. (2023) reported challenges of the substitution with bio-based products, such as higher cost compared to fossil-based materials and low knowledge of those novel materials.

Previous studies identify several issues in the comparison of bio-based and fossil-based products via LCA. Bishop et al. (2021) review LCA studies that compared bioplastics and petrochemical plastics. Their recommendation for LCA practitioners comparing fossil-based and bio-based products in the plastic sector is to include additives in the life cycle inventory unless their contribution to all impact categories is less than 1%. Dams et al. (2023) also identify key issues related to the LCA, such as the lack of emerging bio-based materials in LCA databases, uncertainties regarding end-of-life scenarios, and the gradual emission of carbon over time of bio-based products. Walker and Rothman (2020) highlight the issues of LCA studies comparing fossil-based and bio-based plastics. Some of them are inconsistent end-of-life treatments, differences in accounting for carbon dioxide (CO_2) sequestration, and the allocation of multifunctional product impacts, such as the treatment of co-products. Their recommendation is to ensure that the studies comply with every section of the Product Environmental Footprint (PEF) method of the European Commission (EC) (European Commission 2021).

Summing up, while some previous studies identified substitution challenges for specific bio-based products (Bos et al. 2024; Rinke Dias De Souza et al. 2024), it is unclear what other challenges exist and whether these are different across products and sectors. Moreover, several LCA studies compare specific bio-based products with their fossil-based counterparts and report specific issues encountered in such comparison (Walker and Rothman 2020; Bishop et al. 2021). It is then unclear how the substitution challenges can be successfully addressed in comparative LCA studies. A key research question is thus how to conduct sound comparative LCAs of bio-based products versus their fossil-based counterparts, given the substitution challenges that exist across a broad range of sectors.

In this context, the present study aims to fill this knowledge gap by comprehensively reviewing what are the challenges associated with the substitution of fossil-based materials with bio-based alternatives from a broad perspective that covers five different sectors: construction, packaging, textiles, chemicals, and woodworking. Additionally, the study intends to identify examples of how these substitution challenges can be addressed in LCA. Based on the findings, the study provides concrete recommendations to LCA practitioners who intend to carry out comparative studies of fossil-based versus bio-based products.

2 Methods

We here investigate substitution effects, intended as to what extent and on which basis bio-based and fossil-based are comparable and substitutable, and if they provide equal functionality (Vadenbo et al. 2017).

A two-step review was conducted to answer the research question. Firstly, we compiled a list of challenges, and then scrutinised comparative LCAs of fossil-based products and bio-based alternatives to investigate if and how they had addressed or solved the challenges previously identified. The workflow is illustrated in Fig. 1.

To identify substitution challenges, peer-reviewed articles were selected based on their relevance to the bio-based substitution in five different sectors: construction, packaging, textiles, chemicals, and woodworking. Those sectors were selected because they are prioritised in EU policy frameworks, such as the Circular Economy Action Plan (chemicals, textiles, construction, and packaging) (European Commission 2020). To find relevant articles, Google Scholar was used for a search with keywords "fossil-based vs bio-based" followed by the sector name (e.g., "fossil-based vs bio-based construction"). The objective was to identify two to three highly relevant representative articles per sector that would serve as specific input for expanding the review using an AI-based literature tool. Each search returned a large body of literature: several thousand results per sector, covering a range of topics. Thus, the results were firstly sorted by relevance using Google Scholar's sorting function (based on the search string and the number of citations) and filtered by publication year (after 2015). Based on this sorting, the top 150 results (20–40 per sector) were selected, considering that this number was sufficient to identify a small number of representative articles. Then, the screening based on the article titles narrowed down the literature set from 150 to 20 articles to be used for the second screening. In the second screening, the articles were chosen based on the abstract. Besides giving priority to recent, highly cited articles, the selection focused on those discussing the substitution of fossil-based products with bio-based alternatives or the challenges associated with new bio-based products. This procedure resulted in the selection of 13 representative articles. From this point, the review was expanded using the AI-based tool Research Rabbit to find additional related publications. The tool clusters scientific articles based on the similarity in keywords and authorship by using specific machine learning algorithms, which are, however, not open source (Andrade-Cabrera et al. 2026; Research Rabbit 2026; Personal Communication). One of the intended uses of the Research Rabbit is to take an exemplary article and then identify other articles that are similar to it via the tool's algorithm, and this is also how the tool was used in the present study. More specifically, the 13 representative articles were used as input to the tool and 57 similar scientific articles were identified through its default algorithm. Afterwards, these articles were analysed based on the principle of thematic saturation, an approach used in qualitative research (Saunders et al. 2018), in which the articles are analysed one by one until they do not introduce new findings beyond those already identified. Saturation was assessed by comparing each new identified challenge with the pool of previously identified challenges. The analysis continued until the analysis of new articles did not identify additional challenges, indicating that the thematic saturation was reached, resulting in the additional 31 articles from the tool being included in the review.

In order to examine whether the substitution challenges identified in the literature review are addressed in LCAs, we additionally conducted a literature review of comparative LCAs. Our aim was exploring how existing studies account for those challenges rather than performing a comprehensive review and generalising across all LCAs. Our review did not discriminate based on impact category, thus including all relevant studies regardless of the impact category (or categories) falling in their scope. The investigation of differences across the scope of such studies was beyond the scope

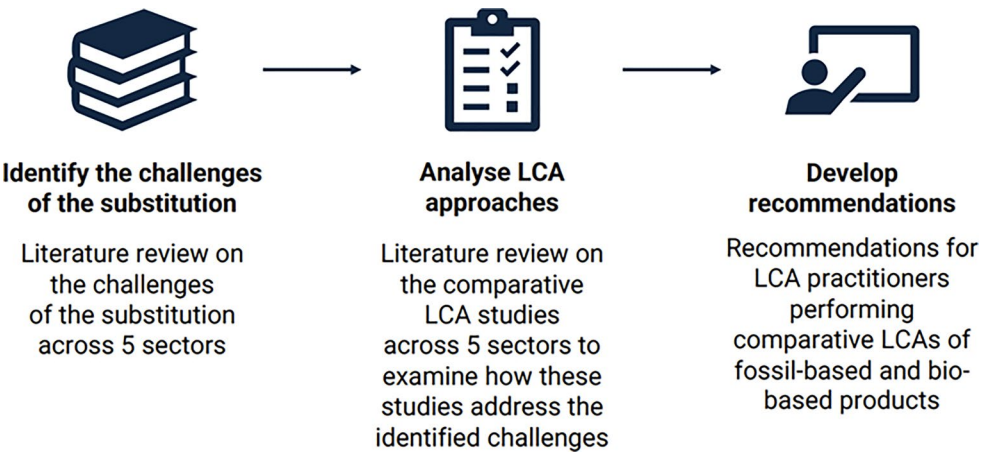

Fig. 1 Schematic representation of the workflow of the study. "5 sectors" in the figure refers to the investigated sectors in the study: construction, packaging, textiles, chemicals, and woodworking

of this review, since the focus was on how the identified challenges were addressed. Several thousand results were initially identified through a Google Scholar search "LCA of fossil-based vs bio-based" followed by the sector name. The review process was conducted in the same manner as the aforementioned review of challenges. First, the search results were sorted by relevance, which narrowed the articles down to 60. These articles were then screened based on the title, which resulted in 17 articles selected for the second screening. In the second screening, these 17 articles were screened based on the abstract, leading to selection of 8 representative articles. The pool of studies was then expanded using the AI-based tool Research Rabbit through its default algorithm. From the output of Research Rabbit, 15 studies have been selected based on their relevance and geographic diversity, ensuring that the studies represent a variety of regional contexts, aiming for four to five studies per sector. This resulted in a total of 23 comparative LCA studies.

A decision tree summarizing the entire review methodology is provided in Fig. 2.

3 Results

3.1 Key substitution challenges

The key challenges in replacing fossil-based products with bio-based alternatives across five sectors are summarized in the following, taking one sector at the time. An overview of the substitution challenges identified in the review and corresponding products affected in each sector is provided in Table 1.

3.1.1 Construction sector

The main challenges in the construction sector relate to the mechanical properties and durability of bio-based materials, such as wood and plant-based insulation, replacing traditional materials, like concrete or mineral insulation. For example, while Cross-Laminated Timber (CLT) is an excellent substitute for fossil-based materials, when used as a main structure, it needs additional treatments for fire resistance, like fireproof coatings or gypsum board, to comply with building codes (2004; Anna-Lisa Östman et al. 2018). Similarly, durability issues of wood, such as ultraviolet (UV) degradation, moisture, and biological damage (e.g., fungi or insects), can be addressed with additional protective coatings ensuring longevity (Nikolic et al. 2015; Reinprecht 2016). However, wood covered with synthetic paint coatings is classified as hazardous waste, which complicates recycling (Sandberg 2016). Acoustic performance can also be a concern for bio-based materials such as CLT, which often require soundboards or additional noise insulation to meet noise standards (Stora Enso 2020). Hygrothermal performance can be another challenge, since timber walls typically require wind and vapour barriers to prevent moisture-related problems (Asdrubali et al. 2017). Moreover, the use of wood for high-rise buildings is complicated by fire safety regulations in some countries that limit its use as a load-bearing material for structures above four stories (Træ i Byggeriet 2023). Bio-based insulation, such as meadow grass, generally has higher thermal conductivity compared to mineral insulation (Gramitherm 2024): thicker layers of insulation are needed to achieve the same thermal performance. Additionally, bio-based materials can be less locally available than concrete and therefore may require longer transportation distances, for example in the case of CLT (Liang et al. 2020). Finally, bio-based construction materials also face regulatory challenges, since hemp, used for insulation, blocks or boards, is still restricted in some countries, and legislative reform is needed to enable its full industrial use (UNCTAD 2022).

3.1.2 Packaging sector

In the packaging sector, different bio-based polymers can have different applications, e.g., starch-based polymers may be used for cups, shopping bags, or foamed trays, while cellulose-based polymers may be used for film wrap for bakery products, and polylactic acid can be used for food containers (Emblem and Emblem 2012; Verghese et al. 2012). In this sector, the main challenges that some bio-based alternatives, such as starch-based products, face are ensuring mechanical properties and moisture sensitivity (Chen et al. 2021). The suitability of some bio-based materials and derived products (e.g., natural biopolymer films) for packaging is limited because they can become unstable in humid environments or when in contact with high-moisture food (Nilsen-Nygaard et al. 2021). The mechanical properties of some bio-based packaging materials and derived products, such as biopolymer films, limit the ability to be processed by industrial methods such as extrusion or film-blowing (Nilsen-Nygaard et al. 2021). Moreover, due to their mechanical and physical properties, bio-based materials, such as starch, may not be suitable for food packaging (Donkor et al. 2023) and since they may not protect the food properly, it can result in higher food spoilage (Conte et al. 2015). In addition to that, nearly all the UV-B and UV-A light can pass through packaging made of polylactic acid (PLA), which can affect food quality (Sari et al. 2021). Some bio-based packaging can also show poor oxygen barrier characteristics (e.g., cellulose-based polymers) and reduced moisture (e.g., polyamide 6 (PA6)) and gas barrier (e.g., styrene acrylonitrile (SAN)) performance compared to

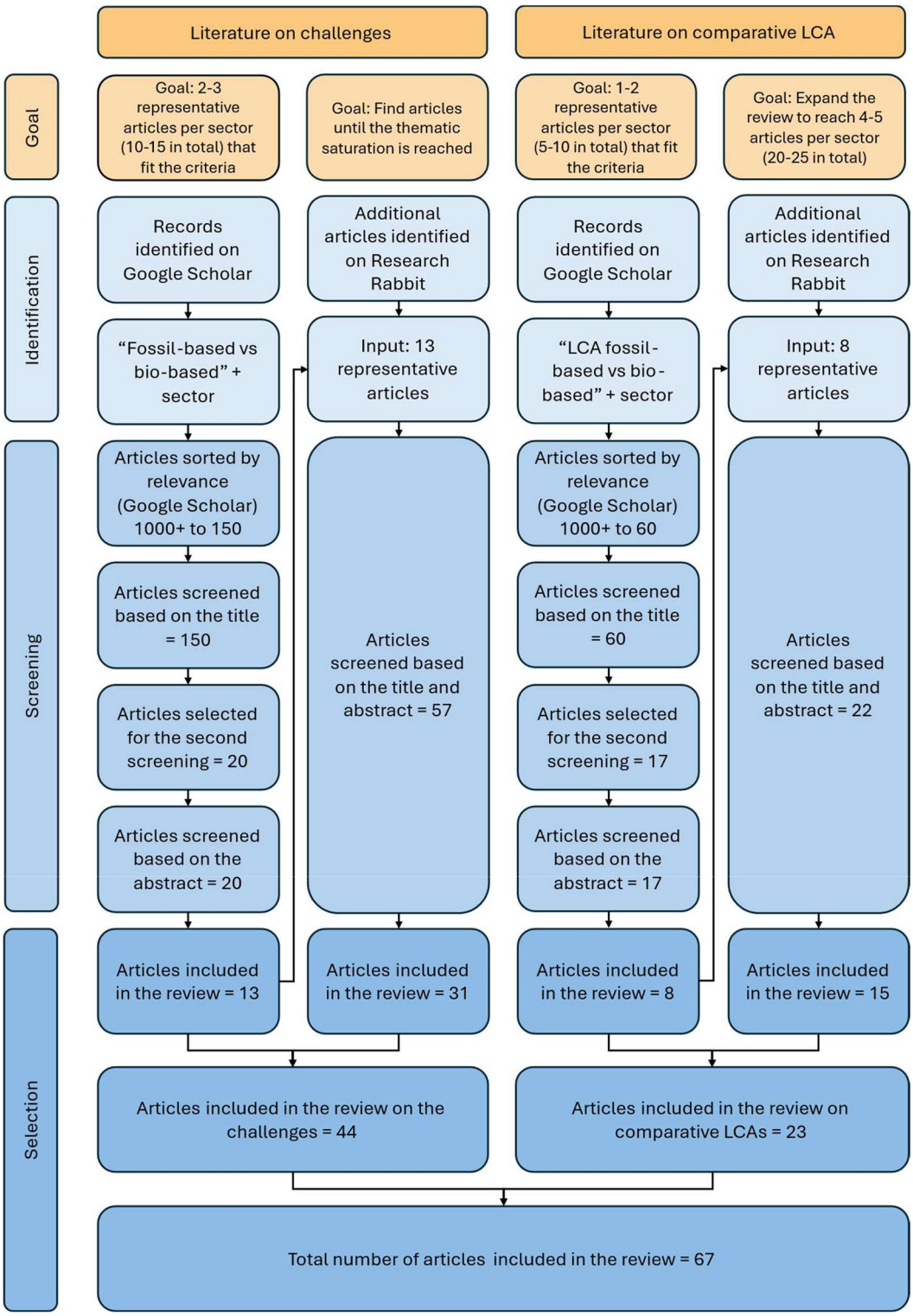

Fig. 2 Decision tree of the methodology. The two left columns refer to the literature review discussing the challenges of the substitution of fossil-based products with bio-based alternatives across 5 sectors: construction, packaging, textiles, chemicals, and woodworking. The phrase "+ sector" in the search string indicates adding one of these sector names to the query. The two right columns refer to the literature review of comparative LCA studies of fossil-based and bio-based products, conducted to explore how these studies addressed previously identified challenges

Table 1 Examples of substitution challenges identified in each sector: construction, packaging, textiles, chemicals, and woodworking, and examples of correspondingly affected products as reported in the literature

Sector	Examples of substitution challenges	Examples of product affected (source)
Construction	Lower fire resistance performance (need for additional treatments/materials)	Timber (2004; Anna-Lisa Östman et al. 2018)
	Ultraviolet degradation, moisture, and biological damage (need for additional coatings)	Timber (Nikolic et al. 2015; Reinprecht 2016)
	Different waste management (hazardous)	Timber (Sandberg 2016)
	Lower acoustic performance	CLT (Stora Enso 2020)
	Lower hygrothermal performance	Timber (Asdrubali et al. 2017)
	Regulatory barriers (i.e., fire regulations)	Timber (Træ i Byggeriet 2023)
	Limited availability	CLT (Liang et al. 2020).
	Worse thermal performance	Meadow grass (Gramitherm 2024)
	Material legislation barriers	Hemp (UNCTAD 2022)
Packaging	Lower Mechanical properties and moisture sensitivity	Starch-based products (Chen et al. 2021)
	Suitability for food packaging	Starch-based products (Donkor et al. 2023)
	Recycling and biodegradation challenges	Starch-based products (Chen et al. 2021)
	Instability in humid environments; Limited ability to be processed by industrial methods	Biopolymer films (Nilsen-Nygaard et al. 2021)
	Limited UV protection	PLA packaging (Sari et al. 2021)
	Poor oxygen barrier characteristics	Cellulose-based polymers (Salwa et al. 2021)
	Reduced moisture barrier performance	Polyamide 6 (Pandit et al. 2018)
	Reduced gas barrier performance	Styrene Acrylonitrile (Emblem 2012)
	Higher cost	PHA packaging (Jõgi and Bhat 2020)
	Seasonal variations in the supply of raw materials	Rice straw packaging (Ibrahim et al. 2021)
	Scalability	Protein-based films (Martins et al. 2021)
	Poor policy support and a lack of industrial composting facilities	Bio-based food packaging in general (Ilyas et al. 2021)
Textiles	Complex processability	Biopolymers (Manvi 2020; Militký et al. 2024)
	Higher cost	Bio-based polyester and bio-based polyamide (Textile Exchange 2024b); Biopolymers (Manvi 2020; Militký et al. 2024)
	Production processes difficulties	Bio-based fibres (Textile Exchange 2024)
	Difference in extensibility, fragility, and strength	Bio-based fibres (Islam et al. 2019; Militký et al. 2024).
	Lower adherence to polymer matrices (need for additional treatments)	Cellulosic fibres (Syduzzaman et al. 2020)
	Significant moisture uptake (need for additional treatments)	Jute (Shahinur et al. 2022)
	Lower fire, water, and UV resistance; Difference in flexibility, elasticity, and softness	Vegan leather (Minh and Ngan 2021)
	Material legislation barriers	Hemp (La Rosa and Grammatikos 2019)
	Low fastness properties, shade reproduction, long extraction procedures, and a limited colour range (need for additional treatments); Difficulties in bonding cotton fibres with natural dyes (need for additional treatments)	Bio-based dyes (Haji and Naebe 2020; Metwally et al. 2021)
	Limited seasonal availability; Colour fading	Plant-based pigments (Isah 2019; Rognoli et al. 2022)
Chemicals	Complex logistics of biomass (storage, handling, and transportation)	Biomass and bio-based chemicals (Clark and Deswarte 2015; Garmulewicz et al. 2022)
	Moisture sensitivity	Straw (Kadam et al. 2000)
	Low energy density (for energetic use)	Biomass (Lam et al. 2015)
	Energy-intensive processing; Need for additional chemicals	Biomass (Fiorentino et al. 2019)
	Technical processing	Algal biomass (Lee and Lavoie 2013)
	Mechanical performance; Durability (need for additional treatments/coatings)	Bio-based composites (Chang et al. 2020)
	Cost; Scalability; Processability	Bio-based polymers (Righetti et al. 2024)
Woodworking	Lower glue strength; Low water resistance (need for crosslinkers)	Starch adhesives (Zhao et al. 2011; Hemmilä et al. 2017)
	Low heat resistance (need for crosslinkers)	Soybean protein adhesives (Zhao et al. 2011)
	Short application period	Tannin adhesives (Zhao et al. 2011)
	High viscosity	Soy-based adhesives (Ghahri et al. 2021).

Table 1 (continued)

Sector	Examples of substitution challenges	Examples of product affected (source)
	Low solid content	Sugar-based adhesives (Ghahri et al. 2021).
	Low reactivity (need for additional treatments)	Lignin adhesives (Hemmilä et al. 2017)
	Lower strength of a final product	Tannin adhesives (Ghahri et al. 2021)
	Higher cost	Bio-based adhesives in general (Dunky 2017)

fossil alternatives (Emblem 2012; Pandit et al. 2018; Salwa et al. 2021). Bio-based packaging can also face challenges in production and supply. The production of some bio-based packaging materials, such as polyhydroxyalkanoate (PHA), can be 5–10 times more expensive than traditional plastic (Jõgi and Bhat 2020), and seasonal variations in the supply of raw materials, like rice straw, can affect production continuity (Ibrahim et al. 2021). While protein-based films are being developed, this technological advancement is not yet scalable to industrial production (Martins et al. 2021). Challenges associated with bio-based plastics depend on the generation of biomass used. The 1st generation feedstocks (food crops, such as corn and sugarcane) compete with food production, while the 2nd generation feedstocks (agricultural residues, such as straw) require an additional step: pretreatment (de Mello et al. 2025). Manufacturing products from the 3rd generation feedstocks (natural algae and cyanobacteria) can be energy-intensive, which increases processing costs (de Mello et al. 2025). Lastly, the 4th generation feedstocks (genetically modified microalgae) are currently performed on a small scale and their production requires high costs (de Mello et al. 2025). Some bio-based packaging solutions, like starch-based products, can also present challenges in terms of recycling and biodegradation. To improve their technical characteristics, such as moisture resistance, bio-based products are occasionally coated or blended with synthetic polymers, which results in them not being biodegradable (Chen et al. 2021). "Bioplastics" are often proposed as potential substitutes in the packaging sector. When comparatively assessing a polymer from two different sources (i.e., biomass vs fossil fuel) the polymer maintains all its technical characteristics. This means that a polymer-specific characteristic, such as biodegradability, is independent from the bio- or fossil-origin of the polymer. However, the term "bioplastic" refers to a material that is bio-based, biodegradable, or both (Pandit et al. 2018), possibly generating confusion. The biodegradability characteristic should be accounted for when comparing two different polymers, where a bio-based solution is compared to a fossil-based counterpart (e.g., PHA vs polyethylene (PE)), rather than the same polymer from different feedstock (e.g., bio-PE vs PE) (Pandit et al. 2018). Even when the bio-based products are claimed to be biodegradable, they might need special conditions to biodegrade (Mohanty et al. 2000), which complicates waste management. Furthermore, other challenges include poor policy support for bio-based packaging of food, as well as the lack of industrial composting facilities and energy recovery equipment in developing countries (Ilyas et al. 2021). Finally, the environmental performance can be sensitive to transportation assumptions due to the higher density of some bio-based materials, e.g., in the case of mycelium-based packaging (Enarevba and Haapala 2023).

3.1.3 Textiles sector

In the textile sector, most challenges occur in the processability area. Biopolymers can be expensive and difficult to process, which limits their use in specific applications (Manvi 2020; Militký et al. 2024). Moreover, due to the differences in properties of bio-based materials and synthetic materials, such as melting point, it may be necessary to change the production processes from synthetic ones, which can be challenging for suppliers who cannot utilise the same machinery as for synthetic materials (Textile Exchange 2024). Additionally, some bio-based materials often require additional treatment, due to the low adherence to polymer matrices (e.g., cellulosic fibres (Syduzzaman et al. 2020)) or due to a significant moisture uptake (e.g., jute (Shahinur et al. 2022)). Bio-based fibres often require additional chemical treatments during production to achieve performance levels comparable to those of fossil-based fibres. These treatments, such as alkaline, silane, benzoylation, peroxide, or permanganate treatments, depend on the fibre type and application. They serve different purposes, including enhancing fibre-matrix and reducing the moisture uptake of the material (Li et al. 2007). Bio-based textiles also face challenges in material properties and performance. They can have limited extensibility, higher fragility, and less strength compared to synthetic materials (Islam et al. 2019; Militký et al. 2024). Bio-based vegan leather faces challenges with fire, water, and UV resistance, flexibility, elasticity, and softness (Minh and Ngan 2021). Regulations are also a challenge for some bio-based materials in textile production. This is the case of hemp, which, even though it is a strong and resistant alternative to synthetic materials, it is illegal to grow industrially in most parts of the world (La Rosa and Grammatikos 2019). In the case of bio-based dyes, challenges arise with low fastness properties, shade reproduction, long extraction procedures, limited colour range, and

cotton fibres struggling to bond with natural dyes making additional treatments necessary (Haji and Naebe 2020; Metwally et al. 2021). Mordanting, which prepares the natural fibre to accept colour (Haji and Naebe 2020), is an example of this kind of additional treatment. Plant-based pigments are dependent on seasonal availability and may experience colour fading over time (Isah 2019; Rognoli et al. 2022). Finally, some bio-based materials (such as bio-based polyester and bio-based polyamide) have higher prices than their fossil-based counterparts (Textile Exchange 2024b).

3.1.4 Chemicals sector

In the chemicals sector, the main challenges with substitution are storage, handling, and transportation of biomass (i.e., feedstock) and bio-based chemicals. Biomass typically has a low bulk density and high water content, which makes the transport in its raw state more expensive (Clark and Deswarte 2015). Moreover, some bio-based materials, such as straw, are susceptible to moisture and ambient conditions and can lead to quality deterioration during storage (Kadam et al. 2000; Garmulewicz et al. 2022). Energy efficiency can also be a challenge for bio-based chemicals. Biomass has low energy density (for energetic use) in comparison to fossil fuel (Lam et al. 2015), and the processing of biomass in bio-refineries is often energy-intensive and requires the consumption of additional chemicals (Fiorentino et al. 2019). Bio-based chemicals also face technical processing challenges. For instance, dewatering is required before lipid extraction in the production of algal biomass due to its high water content (Lee and Lavoie 2013). Technical performance is another limitation, as bio-based composites (a blend of two or more bio-derived materials (Raeisi et al. 2024)) tend to have lower mechanical performance and durability than traditional materials (Chang et al. 2020). However, strategies such as proper biofillers (used to make bio-based composites more durable) selection, and surface modification, like additional exterior coatings, can enhance their durability (Chang et al. 2020). Economic viability remains another hurdle, as bio-based polymers often struggle with cost-effectiveness, scalability, and processability (Righetti et al. 2024). Lastly, the lack of cost-efficient scaled-up processes and lower performance make bio-based alternatives less competitive compared to fossil-based technologies (Calvo-Flores and Martin-Martinez 2022).

3.1.5 Woodworking sector

In the woodworking sector, the major limitation of using bio-based adhesives is performance, as some of them can have lower glue strength and reduced resistance to water (e.g., starch-based adhesives) and heat (e.g., soybean protein adhesives), along with short application periods (e.g., tannin adhesives) (Zhao et al. 2011; Hemmilä et al. 2017). Low solid content (e.g., sugar-based adhesives) and high viscosity (e.g., soy-based adhesives) of some bio-based adhesives can complicate production (Ghahri et al. 2021). Some bio-based adhesives have low reactivity (e.g., lignin adhesive), which requires modification to achieve the required bonding strength and longer pressing times, which can cause the overall production costs to increase (Hemmilä et al. 2017). Moreover, due to their chemical properties, there is a risk of an undesirable interaction when mixing some bio-based adhesives (e.g., tannin adhesives) with other chemicals, which can reduce the strength of the final product (Ghahri et al. 2021). In addition to performance issues, bio-based adhesives can present manufacturing and cost-related challenges (Dunky 2017). To compete with synthetic adhesives, bio-based alternatives must lower costs and improve their reaction speed (Dunky 2017).

3.2 Addressing substitution challenges in LCA: key examples from current practice

Results of the literature review highlight how fossil-based products and their bio-based alternatives are often not directly substitutable. The factors affecting the substitutability should be considered when carrying out a comparative LCA. Based on the review of LCA studies (cf. Fig. 2) in the following selected examples of comparative LCAs of bio-based products versus fossil-based counterparts are analysed describing whether and how the substitution challenges identified were addressed. A summary is provided in Table 2 sector-wise.

3.2.1 Construction sector

To compare bio-based and fossil-based construction materials, Liang et al. (2020) perform a comparative LCA of a mass timber building and a concrete alternative on a 12-story mixed-use apartment/office building in the United States. The study addresses challenges of differences in fire resistance and thermal performance by ensuring the functional equivalence in fire-proofing performance, insulation, and energy consumption outcomes compared to the concrete design. Additionally, the study also addresses the challenge of differences in local availability of materials by including the transportation distances in the inventory. Similarly, Pierobon et al. (2019) compare a hybrid CLT commercial building and a concrete building with a similar function. In their study, the challenge of differences in the fire resistance is addressed by ensuring comparability in terms of fire protection via two alternative designs. The CLT building's structural properties are optimised, however, they do not

Table 2 Technical challenges identified in each sector: construction, packaging, textiles, chemicals, and woodworking, and how they are addressed in the analysed comparative LCA studies

Sector	Substitution challenge (bio-based vs fossil-based)	LCA studies that addressed the challenge	Methodological solution
Construction	Difference in fire resistance	Liang et al. (2020), Pierobon et al. (2019), Rinne et al. (2022), Schulte et al. (2021)	Ensuring functional equivalence: fire resistance requirement specified in the functional unit; Adjusting the reference flow to achieve functional equivalence in terms of fire resistance
	Worse thermal performance	Liang et al. (2020), Schulte et al. (2021)	Ensuring functional equivalence: thermal resistance requirement specified in the functional unit; Adjusting the reference flow to achieve functional equivalence in terms of thermal performance
	Difference in acoustic performance	-	Not covered by the cases under analysis
	Difference in local availability	Liang et al. (2020), Pierobon et al. (2019), Sandanayake et al. (2018)	Difference in local availability addressed by specifying transportation distances
	Difference in durability (UV, moisture)	Schulte et al. (2021)	Adjusting the reference flow to achieve functional equivalence in terms of differences in durability by specifying lifetime and protective measures
	Different waste management (hazardous)	Schulte et al. (2021)	Including the analysis of the waste materials and expanding the system boundary to include disposal stage
	Regulatory barriers	-	Not covered by the cases under analysis
Packaging	Difference in mechanical properties (e.g., moisture sensitivity)	-	Not covered by the cases under analysis
	Need for coatings/additional treatments	-	Not covered by the cases under analysis
	Difference in UV light permeability	-	Not covered by the cases under analysis
	Difference in suitability for food packaging	Tamburini et al. (2021), Cappiello et al. (2022)	Suitability for food packaging specified as requirement in the functional unit
	Recycling and biodegradation challenges	Tamburini et al. (2021), Cappiello et al. (2022), Enarevba and Haapala (2023), Günkaya and Banar (2016)	Recycling differences addressed by including various end-of-life scenarios and expanding the system boundary to include disposal stage.
	Lack of supply continuity	-	Not covered by the cases under analysis
Textiles	Difference in production processes	Van Der Velden et al. (2014), Gonzalez et al. (2023), Institute for Sustainable Resources (2009), Egorova et al. (2014)	Modelling a detailed product system for each of the compared products
	Difference in material properties	-	Not covered by the cases under analysis
	Lower fire, water, and UV resistance	-	Not covered by the cases under analysis
	Biodegradability challenges	-	Not covered by the cases under analysis
	Need for additional treatments	Van Der Velden et al. (2014), Institute for Sustainable Resources (2009)	Additional treatments included in the product system
	Seasonal availability variations	-	Not covered by the cases under analysis
	Material legislation barriers	-	Not covered by the cases under analysis
Chemicals	Complex logistics of biomass (storage, handling, and transportation)	Gian et al. (2022), Mu et al. (2010)	Logistics included in the product system
	Higher susceptibility to moisture and ambient conditions	-	Not covered by the cases under analysis
	Need for additional treatments	Mu et al. (2010), Gian et al. (2022), Fiorentino et al. (2019)	Additional treatment activities included in the product system
	Lower mechanical performance and durability	-	Not covered by the cases under analysis
	Lack of scalability	Alvarenga et al. (2013), Gian et al. (2022), Fiorentino et al. (2019)	Scalability addressed through uncertainty analysis
	Difference in technical processing	Gian et al. (2022), Fiorentino et al. (2019), Mu et al. (2010), Alvarenga et al. (2013)	Technical processing included in the product system

Table 2 (continued)

Sector	Substitution challenge (bio-based vs fossil-based)	LCA studies that addressed the challenge	Methodological solution
Woodworking	Lower adhesive performance (e.g., bond strength)	McDevitt and Grigsby (2014)	Adjusting the reference flow to achieve functional equivalence in terms of adhesive performance
	Processing challenges (e.g., solid content)	-	Not covered by the cases under analysis
	Need for crosslinkers or additional treatments	Arias et al. (2020), Arias et al. (2022)	Inputs of crosslinkers included in the product system

match the exact performance requirements of the concrete building since the standard loading requirements are used instead, therefore the CLT building cannot be described as functionally equivalent. The study also addresses the challenge of differences in local availability by specifying the transportation distances in the inventory. Sandanayake et al. (2018) also perform a comparative LCA study of a concrete and timber building. The timber building in the study is modelled based on a building existing in the United Kingdom (UK) context and adapted to the Australian one, due to the lack of examples in the Australian context. However, the only adjustments are made to reflect materials availability in Australia, and construction equipment – after surveying local contractors – while material quantities are not adjusted, failing to capture the significant climate differences between the two countries. In their case study, they address the challenge of differences in local availability by specifying the transportation distances in the inventory. Rinne et al. (2022) compare hybrid, concrete, and timber apartment buildings in Finland. The study addresses the challenge of differences in fire resistance by ensuring that the Finnish fire building regulations are fulfilled in the investigated buildings. Schulte et al. (2021) perform an LCA of four bio-based insulation materials: wood fibre, hemp fibre, flax, and miscanthus, and two non-renewable insulation materials: expanded polystyrene (EPS) and stone wool. The challenges of differences in fire resistance, thermal performance, and differences in durability are addressed by specifying them as a requirement in the functional unit "*insulating 1 m^2 of an external wall of a residential building with 0.24 W $m^{-2}K^{-1}$ for 70 years, fulfilling legal fire resistance and health and safety standards*" (Schulte et al. 2021). The challenge of differences in waste management is addressed by expanding the system boundary to include the disposal phase and modelling the end-of-life scenarios, accounting for the hazardous waste due to the use of flame retardants.

3.2.2 Packaging sector

Tamburini et al. (2021) and Cappiello et al. (2022) investigate the environmental impact of beverage packaging through comparative LCA. Tamburini et al. (2021) compare polyethylene terephthalate (PET), bioplastic (PLA), and refillable aluminium bottles for drinks, meanwhile Cappiello et al. (2022) compare a PLA bottle, a PET bottle, a high-density polyethylene (HDPE) bottle, a multilayer carton, and a glass bottle. Both studies address the difference in suitability for food packaging between fossil-based packaging and bio-based alternatives by specifying it as a requirement in the functional unit *"containing beverage for consumption for one year of use"* (Tamburini et al. 2021) and *"the packaging needed to contain 1 L of ESL milk and to guarantee a shelf life of 30 days"* (Cappiello et al. 2022). Additionally, both studies also address the recycling and biodegradation challenge by expanding the system boundary to include the end-of-life phase, and modelling various end-of-life scenarios. Tamburini et al. (2021) model the following end-of-life scenarios: recycling, unsorted waste, incineration, landfill for the PET bottle, and composting and incineration for the PLA bottle, while Cappiello et al. (2022) model: recycling, composting, and landfill. Similarly, both Enarevba and Haapala (2023) and Günkaya and Banar (2016) focus on packaging materials. Enarevba and Haapala (2023) examine shipping box inserts made from EPS and mycelium, additionally including transportation assumptions in their research. Instead, Günkaya and Banar (2016) focus on biocomposite film and low-density polyethylene (LDPE) film. Both studies address the recycling and biodegradation challenge. Enarevba and Haapala (2023) do it by expanding the system boundary to include the end-of-life stage (gate-to-grave) across different scenarios: landfilling, recycling, and incineration for EPS, and two methods of composting for the mycelium. Günkaya and Banar (2016) address the recycling challenge by evaluating the biodegradation of the films in an experimental simulation.

3.2.3 Textile sector

Van Der Velden et al. (2014) conduct a comparative LCA of cotton, polyester, nylon, acryl, and elastane to compare their environmental performance. They address the challenges of differences in production processes between the bio- and fossil-based products and the need for pretreatments in bio-based products by modelling a product system that includes material-specific production routes and including the necessary pretreatments for bio-based products based on the

literature and private communication. Similarly, Gonzalez et al. (2023) compare six materials: conventional and organic cotton, silk, jute, flax, and polyester, addressing the challenge of differences in production processes between the bio- and fossil-based products by using material-specific product systems from Ecoinvent, which include differences in agricultural and industrial production routes. While Egorova et al. (2014) compare cotton, wool, polyester, and lyocell T-shirts, Institute for Sustainable Resources (2009) looks into 100% cotton and 100% polyester T-shirts. Both studies address the challenge of differences in production processes between the bio- and fossil-based products. Egorova et al. (2014) address this challenge by creating the life cycle inventory based on the supplier's data that include fibre-specific processes. The study made by Institute for Sustainable Resources (2009) addresses the same challenge by modelling a product system that specifically includes the additional processing steps for bio-based products. Different functional units are used for the studies: 1 kg of (greige) textile (Van Der Velden et al. 2014), 1 kg of raw material, 1 kg of yarn, and 1 kg of dyed fabric (Gonzalez et al. 2023), 75 wears of an everyday t-shirt (once a week, for 1.5 years) (Institute for Sustainable Resources 2009), and 1 million T-shirts (Egorova et al. 2014). The choice of a functional unit can significantly influence the outcome of the assessment. For instance, weight-based comparisons (i.e., 1 kg of raw material) can be misleading, since the output (such as the number of T-shirts) may vary significantly.

3.2.4 Chemicals sector

Mu et al. (2010) conduct LCA of biochemical and thermochemical processes from the perspective of lignocellulosic ethanol production, while Gian et al. (2022) focus on the biochemical and thermochemical processes to produce bio-based purified terephthalic acid (PTA). Both studies address the challenges of the complex logistics of biomass, the need for additional treatments of bio-based products, and differences in technical processing by including in the product system specific logistics and treatment processes and adjusting them to reflect the technical differences required by the bio-based production. Gian et al. (2022) additionally address the scalability challenge by quantifying the influence of low technological maturity data through a pedigree matrix uncertainty analysis. Fiorentino et al. (2019) compare biofuels and bio-ethylene with fossil fuels and fossil ethylene, addressing the need for additional treatments of biomass by including such additional biomass treatment processes in the product system. The study also addresses the challenge of scalability by analysing different future improvement scenarios. The study also addresses the challenge of differences in the technical processing of bio- and fossil-based products by modelling a product system that represents product-specific processing steps and chemical routes. Alvarenga et al. (2013) compare bioethanol-based and fossil-based polyvinyl chloride (PVC), addressing the challenge of differences in technical processing of bio- and fossil-based products by modelling distinct product-specific production routes based on the literature and Ecoinvent database. The challenge of scalability is addressed by analysing scenarios for future improvement.

3.2.5 Woodworking sector

Arias et al. (2020) compare soy-based, kraft lignin-based, organosolv lignin-based, and pine tannin-based adhesives with urea-formaldehyde (UF), phenol-formaldehyde (PF), and melamine urea-formaldehyde (MUF) adhesives. McDevitt and Grigsby (2014) compare a lignin-protein adhesive with a fossil-based one made of urea formaldehyde resin. Arias et al. (2022) compare five tannin-based adhesives with fossil-based adhesives (UF, PF, and MUF) and Yang and Rosentrater (2021) compare the production of structural bio-adhesive derived from bio-glycerol and the production of structural adhesive derived from petro-glycerol. Arias et al. (2020) and Arias et al. (2022) address the challenge of the need for crosslinkers or additional treatments in bio-based products by including such crosslinkers and treatments in the product system. Meanwhile, McDevitt and Grigsby (2014) address the lower adhesive performance of bio-based alternatives by adjusting the reference flow to achieve functional equivalence in terms of adhesive performance. Yang and Rosentrater (2021) do not specify whether the previously identified challenges were addressed in the case study.

4 Discussion

The study answers the research question by offering a comprehensive view on the substitution of fossil-based materials with bio-based alternatives, analysing technical, economic, and regulatory challenges across multiple sectors, as well as examining how these challenges are tackled in comparative LCA studies. While the literature focuses on individual products, this study focuses on sectors, considering multiple products and industries with similar characteristics.

Given that results rely only on a review of published studies, they may not capture all the challenges that exist in real-world practices. Results are aggregated at the sector level, but not all industries or products within the same sector might necessarily face the same challenges. For instance, local conditions, such as the geographic availability of raw materials, can significantly limit the use of bio-based

materials due to transportation costs. A material that is common in one region may be scarce in another, leading to different economic and logistical barriers, even within the same sector. On top of that, most of the analysed case studies are from countries with established infrastructure that can support bio-based supply chains, such as Finland (Rinne et al. 2022), Italy (Cappiello et al. 2022) or the Netherlands (Van Der Velden et al. 2014). Supply-related challenges may be more significant in countries with less established logistical and industrial conditions. For instance, supply chain networks, regulatory support, and processing facilities differ across countries, which leads to differing challenges in adopting bio-based products. Another limitation is a disproportionate focus on the comparative LCA studies within the construction and packaging industries, while the chemical industry remains significantly underrepresented in comparison to other sectors.

As shown in Table 2, several comparative LCA studies across the five sectors have addressed challenges associated with local availability, recycling, scalability, material properties, and structural integrity. However, other challenges, such as the need for additional treatments or coatings, supply continuity, or environmental durability (e.g., UV and water resistance), were not addressed in the comparative LCA studies considered in this analysis.

As summarized in Table 2, the substitution challenges can be addressed in LCA studies in many ways. Some challenges, such as differences in fire resistance, thermal performance, or adhesive performance, can be addressed by integrating these technical characteristics into the functional unit. Other challenges, like the need for additional treatments, can be solved by including dedicated activities in the product system. Challenges, such as accounting for waste management and recycling, can be tackled by expanding the system boundary and doing scenario modelling. Lastly, challenges such as unclear scalability can be addressed by performing uncertainty analysis.

From an LCA perspective, these results show that some issues identified in the literature review, such as incorrect definition of the functional unit, using an incomplete life cycle inventory, or excluding certain phases of the product chain, are of a general methodological nature and can occur in any LCA study. Without addressing them, the assessment can result in a biased comparison. Nevertheless, solving these methodological issues becomes particularly relevant in the LCA of bio-based products due to the specific challenges identified in the review, such as differences in material and mechanical properties between fossil and bio-based alternatives, the need for additional treatments, differences in processing, and compliance with regulations.

Comparative LCA studies of fossil-based and bio-based products might be complicated by additional issues than addressing substitution challenges, that were not considered within the scope of this study. For example, the comparison should account for differences in the technological maturity of the fossil-based and bio-based production systems. Fossil-based materials are well-established and mature technologies, while bio-based materials are new technologies with potential for improvement (European Commission et al. 2021). LCA studies comparing fossil-based and bio-based products often show inconsistencies in the methodological aspects, such as the definition of functional unit and system boundaries, which can lead to biased comparisons (Muthu 2015). Moreover, some of these LCA studies simplify the comparisons by assuming identical usage and disposal for all products, regardless of their properties or purpose (Laitala et al. 2018).

The study has some limitations that should be considered. The conducted review was not intended to be exhaustive- the goal was to identify recurring challenges rather than analyse in detail specific studies rather than the whole body of available literature. Only a limited number of search strings was used and the initial screening was focused on a small number of representative articles. As a result, and despite reaching saturation in the analysis of the selected studies, there is a possibility that some challenges may not have been identified and addressed. Additionally, the use of the AI-based tool Research Rabbit for expanding the literature might introduce some bias, since the tool's algorithm is not transparent. Lastly, it was not possible to link all identified challenges to a specific approach to address them, based on the information found in the reviewed literature. The absence of those approaches does not imply that none of the studies have addressed them, but rather that those studies may not have been included in the selected literature.

5 Conclusion

The results indicate that in some sectors, bio-based materials do not offer the same technical performance, durability, and availability as their fossil-based counterparts. They are characterised by more complex processability and the need for additional treatments. These aspects should be accounted for in comparative LCAs as they affect the results.

This study identified several methodological approaches to account for substitution challenges in the context of LCA. These results align with the findings of previous studies made by Bishop et al. (2021), Rinke Dias De Souza et al. (2024), and Bos et al. (2024).

Building on these findings, we put forward the following recommendations for conducting a comparative LCA of fossil-based materials and their bio-based alternatives. These recommendations are general and applicable across

all sectors, but provide sector-specific examples to illustrate their implementation in diverse contexts. The recommendations are classified based on the ISO phases of an LCA.

5.1 Recommendations for the goal and scope phase

- Ensure functional equivalence: State in the functional unit the needed requirement of the material, such as:
- Construction: Load-bearing capacity, fire resistance, acoustic performance, thermal resistance, and lifetime based on the building standards and intended application.
- Packaging: Moisture resistance, mechanical strength, shelf life, food safety, light transmission, and suitability for specific applications.
- Textiles: Mechanical strength, colour retention, water resistance, thermal insulation, flexibility, yarn thickness, density, and function.
- Chemicals**:** Fatigue strength and moisture absorption.
- Woodworking: Glue strength, water and heat resistance, and application performance.
- Include compensatory measures: Incorporate additional processes or materials required for bio-based substitutes to match fossil-based performance, such as:
- Construction: Fireproofing layers (gypsum board, fire-retardant treatments); acoustic insulation layer or soundboards; moisture barriers; protective coatings to enhance durability and resistance to UV light, water, or wear.
- Packaging: Synthetic coatings that enhance resistance to water, moisture, grease, oxygen, and odour.
- Textiles: Adhesion enhancers and mordant treatments.
- Chemicals: Exterior coatings or biofillers.
- Woodworking: Synthetic crosslinkers.
- Define system boundary cradle-to-grave: include all life cycle stages (raw material extraction, production, transportation, installation, use-phase maintenance, and end-of-life processing) to prevent misleading conclusions, such as overlooking end-of-life impacts, which can significantly affect the comparison of the materials.

5.2 Recommendations for the life cycle inventory phase

- Include end-of-life considerations: Specify disposal or recycling methods, addressing challenges such as:
- Hazardous waste classification (e.g., due to compensatory measures such as fire retardants in construction, or coatings in packaging)
- Recycling barriers for bio-based materials with synthetic additives.
- Whether the material is biodegradable or non-biodegradable and the conditions under which biodegradation occurs (e.g., industrial composting, natural environments).
- Account for transport and local availability: Include transport distances and related emissions, particularly for bio-based materials with limited local supply (e.g., regional fluctuations in textiles or biomass for chemicals).
- Address maintenance requirements: Include material and energy inputs for ongoing maintenance, such as:
- Construction: Protective coatings for durability.
- Textiles: Re-dyeing of low-fast textiles.
- Account for production and preprocessing needs and differences, including:
- Construction: Fireproofing, acoustic treatments, or protective coatings to meet safety and durability standards.
- Packaging: Additive applications (e.g., synthetic coatings to enhance durability).
- Textiles: Additional treatments (e.g., mordanting for plant-based dyes).
- Chemicals: Biomass drying and sorting.
- Woodworking: Extended pressing times or low reactivity challenges.
- Consider indirect impacts: Account for sector-specific implications, such as:
- Packaging: Increased food spoilage from shorter shelf life.
- Textiles: Higher material consumption due to reduced durability.

5.3 Recommendations for the life cycle impact assessment phase

- Evaluate multiple impact categories (e.g., both climate impact and toxicity): For example: consider the trade-offs of using additives and their disposal implications, such as:
- Construction: Fire retardants.
- Packaging: Synthetic coatings.
- Textiles: Adhesion enhancers.
- Chemicals: Coatings.
- Woodworking: Crosslinkers.
- Analyse maintenance and durability impacts: Quantify emissions and environmental costs associated with frequent maintenance or reduced material lifespan (e.g., bio-based adhesives requiring reapplication in woodworking).
- Carefully account for the impact of biogenic carbon. For example, where relevant (e.g., in construction), include the carbon sequestration potential of bio-based materials that remain in the economy for substantially long timeframes.

5.4 Recommendations for the interpretation phase

- Contextualise results: Put the results in perspective, highlighting the environmental benefits and challenges of bio-based alternatives compared to fossil-based adhesives, addressing challenges like limited composting infrastructure for packaging or supply variability for chemicals, packaging, textiles, and woodworking.

- Assess environmental impacts across different categories and functional performance trade-offs. For example: examine the toxicity impacts of chemicals and additives used in bio-based products (necessary to ensure the same performance) and assess whether these are justified by the overall climate benefits of the materials.
- Identify scalability limitations: Discuss challenges like early development stages of bio-based substitutes or fluctuations in supply (e.g., seasonal availability of plant-based dyes for textiles).

Based on the results we also suggest specific directions for further research. More quantitative studies are needed focusing on how including (or leaving out) the aspects recommended in this study influences the results of comparative LCAs between bio-based and fossil alternatives. Comparing the outcomes with and without incorporating those aspects can provide a clear insight into their significance. Another research area of interest for future comparative LCA studies is modelling more closely the End-of-Life stage of bio-based materials, especially their biodegradability and recycling potential when combined with synthetic additives.

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Declarations

Generative AI and AI-assisted technologies in the writing process During the preparation of this work the authors used Jenni and Paperpal to improve the fluency of the language and correct grammar. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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