CALIMERO

IMPROVING BIO-BASED INDUSTRIES LIFE CYCLE SUSTAINABILITY

D2.5

Key levers for improvement of sustainability assessment methodology (public version)

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CONTENTS

PROJECT INFORMATION

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Acronym: CALIMERO

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List of participants:

Partner No.	PARTICIPANT ORGANIZATION | ACRONYM
1 (Coord.)	Contactica | CTA
2	WeLOOP | WELOOP
3	European Cellulose Insulation Association | ECIA
4	Swedish Environmental Research Institute | IVL
5	Neovili | NEOVILI
6	Cesefor | CESEFOR
7	Luxembourg Institute of Science and Technology | LIST
8	Technical University of Denmark | DTU
9	Techtera | TECHTERA
10	Essity | ESSITY
11	BIM Kemi AB | BIMKEMI
12	Ereks garment| EREKS

LIST OF ACRONYMS

AHP	Analytic hierarchy process
CF	Characterisation factor
CFF	Circular Footprint Formula
CO_2	Carbon dioxide
CO_2-eq	CO_2 equivalents
D	Deliverable
eLCC	environmental Life Cycle Costing
EoL	End of Life
EPD	Environmental Product Declarations
ES	Ecosystem service
Ethene-eq	Ethene equivalents
FU	Functional Unit
GHG	Greenhouse gas
GJ	Gigajoule
GO	Guarantees of Origin
GWP	Global Warming Potential
GWP_{100}	GWP over a 100-year time period
IAQ	Indoor Air Quality
iLUC	indirect land use change
IO	Input/output
ISO	International Standardisation Organisation
JCP	Job Creation Potential
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCSA	Life Cycle Sustainability Assessment
LULUC	Land use and land use change
N_2O-eq	Nitrous oxide equivalents
NREU	Non-Renewable Rnergy Use
PEF	Product Environmental Footprint
PEFC	Program for Endorsement of Forest Certification
PHA	Polyhydroxyalkanoates
PO_4-eq	Phosphate equivalents
PR	Period Report
SHDB	Social hotspots database
S-LCA	Social Life Cycle Assessment
SO_2-eq	Sulphur dioxide equivalents
SRF	Solid Recovered Fuels
SSbD	Safe and Sustainable by Design
T	Task
WHO	World Health Organization
WP	Work Package

DELIVERABLE DETAILS

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Abstract:	This deliverable (a public version of D2.4) summarizes the findings from T2.4 in CALIMERO related to key levers for improvement of Life Cycle Sustainability Assessment (LCSA) methodology for each of the bio-based sectors included in the project (i.e., construction, woodworking, pulp and paper, textiles, and biochemicals). The results comprise looking into current gaps in assessment methodology, key levers to improve these, and further work needed within the project based on the results.

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1 INTRODUCTION

1.1 Context and aim

The CALIMERO project focuses on improving the sustainability performance and sustainability assessment methodology within the five European bio-based industries of construction, woodworking, textiles, pulp and paper as well as biochemicals. The project is a collaboration between academic partners from research institutes and universities, and industrial partners within the bio-based sectors, as listed in the project information (see page 3).

Within the objective to improve the assessment methodology, the CALIMERO work is focused towards improving current Life Cycle Sustainability Assessment (LCSA) methodologies such as the Product Environmental Footprint (PEF) methodology for environmental Life Cycle Assessment (LCA), economic assessments through Life Cycle Costing (LCC) as well as social assessments through social LCA (S-LCA). The improvement of the assessment methodology will be carried out through developing missing Characterization Factors (CFs) to assess biodiversity loss, impacts to ecosystem services and toxicity effects of sector-specific substances or improving allocation methods, among others.

This Deliverable (D) focuses on the work within Task (T) 2.4 in the CALIMERO project. T2.4 is included within Work Package (WP) 2, which will hand over to the improvement of the assessment methodology taking place in WP3. The aim of T2.4 is to identify key levers for improvement of such sustainability assessment methodology for each of the bio-based sectors included in the project. The focus of the assessment methodology is on all three dimensions of sustainability (i.e., environmental, social and economic). In this report, the findings from Task 2.4 are shown and discussed, including looking further into the current gaps in the assessment methodology, key levers to improve these, and further work needed within the project based on the results.

1.2 Structure of report

The remainder of this report is structured as follows. Section 2 describes the main method and materials used within T2.4. In Section 3, the findings on methodological gaps and levers are shown and discussed. In this regard, the results and discussion are presented for each of the five sectors individually. This section also includes a summary of further work needed within the CALIMERO project based on the findings. Finally, Section 4 provides the main conclusions from each sector.

2 METHOD AND MATERIALS

The main methodologies employed in T2.4 were a literature review, as well as contact and discussions with industrial partners and other companies within the bio-based sectors in the CALIMERO project.

With regards to the literature review, each academic partner performed a scanning of relevant scientific and grey literature, focusing on the sector-specific methodological gaps in assessment methodology for environmental, social and economic perspectives.

In order to get an overview of the gaps and levers within assessment methodology considered important by the sectors included in the CALIMERO project, each academic partner contacted the applicable industrial partner as well as a number of relevant companies within each sector. The aim of the discussions was both to look into the results from the literature review, as well as to gather additional perspectives from the sectors. Moreover, in the discussions with industrial partners, this also included looking into previous results within the CALIMERO project (i.e., discussing gaps identified in case studies performed in T2.1 within WP2), and levers to address these. As a basis for the discussions, a template of questions was drafted within the consortium to be used in the discussions. The template is shown in the Appendix.

3 RESULTS AND DISCUSSION ON METHODOLOGICAL GAPS AND LEVERS

3.1 Construction sector

3.1.1 Literature review of methodological gaps in the construction sector

Considerations on the LCSA framework

Establishing a framework that systematically covers the three pillars of sustainability is one of the main methodological challenges relevant to address in the construction sector. The EN 15804+A2 standards frames the environmental LCA for construction works; it does not aim to address the economic and social spheres. In addition, this normative approach to LCA can be questioned regarding various methodological aspects, such as the dynamic carbon footprint and the accounting of circularity. Indeed, one specificity of the construction sector is the relatively long lifetime of products, which calls for dynamic modelling of the system in life cycle approaches, especially when it comes to the modelling of the sequestered carbon. Buildings can comprise an important share of bio-based materials, especially wood, and typically last at least 50 years (CEN-TC88-WG2, 2014; RE2020). Regulations pushing towards low carbon footprint buildings like the Environmental Regulation 2020 (RE2020) in France encourage the use of bio-based materials, that become increasingly necessary to meet the regulation's objectives. The same regulation imposes a dynamic modelling of the carbon footprint. However, this approach is not consensual, and the ISO14040: 2006 and different guidelines (e.g., International Life Cycle Data System (ILCD) handbook, PEF, and the Guidelines for LCA of Carbon Capture and Utilisation - LCA4CCU) recommend or impose different methodologies to account (or not allow counting) for the temporality of carbon storage and emissions.

LCA methodological gaps

Assessment of biogenic carbon

Three main approaches have been highlighted in LCA literature for accounting for biogenic carbon in the construction sector, based on how the timing of its sequestration and release into the atmosphere is considered. The 0/0 approach, commonly used in Environmental Product Declarations (EPDs) and in the PEF method, disregards the storage or release of biogenic carbon over time. The biogenic carbon neutrality (-1/+1) approach, as outlined in EN 15804+A2, accounts for biogenic carbon sequestration as a negative value (-1) during the production phase, and as a positive emission (+1) at the End-of-Life (EoL) stage, leading to a net zero carbon impact over the product's lifecycle.

Variations of this method, like the -1/+1* approach applied to recycling or landfill EoL scenarios, could be used to assess the permanent biogenic carbon storage for landfill and continued carbon storage in recycled materials. This approach also allows for tracking the biogenic flows through different product systems. It should be pointed out that according to the present version of EN 15804+A2, the effect of permanent biogenic carbon storage shall not be included in the calculation of the GWP. This rule could be interpreted in a way that any transfer of biogenic carbon to another product system would have to be reported as an emission according to EN 15804+A2, irrespective of any arrangement undertaken for carbon capture and utilisation. Potentially, this rule will be reconsidered and changed in the upcoming revision of EN 15804 standards.

The other issue with this method is that consideration of -1/+1 alone will not lead to account for the timing between carbon sequestration and release, which can be significantly long, particularly for wood used in construction products. The biogenic carbon neutrality method oversimplifies biogenic carbon cycles by ignoring temporary imbalances, underscoring the importance of developing dynamic LCA methods (Hoxha et al., 2020).

A particularly relevant aspect for wood-based construction materials or other long term biobased materials is how to account for biogenic carbon stored for over 100 years (ILCD handbook), often referred to as long-term carbon storage (100 < Long-term < ∞) or Quasi-permanent storage (∞). These materials delay carbon release into the atmosphere, potentially qualifying for credits in environmental assessments. The latest European Commission guidelines (2021) suggest future updates will address this topic, but until then, both temporary and permanent carbon storage, along with delayed emissions, are to be considered as 'emitted now,' with no time-based discounting applied (Claudiane et al., 2023).

It's important to highlight that temporary and permanent carbon storage are essential to value the recycling of the bio-based products (in multiple cycles) compared to incineration with energy recovery.

Land use sub-indicators

As highlighted by recent studies, Land Use and Land Use Change (LULUC) play a significant role in carbon sequestration, biodiversity and ecosystem services. Currently, only direct land use change is calculated in PEF methodologies, since for indirect land use changes (iLUC) an agreed methodology, it is still not available. Evaluating iLUC requires accounting for land use shifts that occur outside the system boundaries, such as when agricultural expansion in one area leads to activity displacement in another region (Zampori and Pant, 2019).

Even though this sub-category accounts for carbon uptakes and emissions originating from carbon stock changes and includes biogenic carbon exchanges from deforestation, road construction or other soil activities, it faces challenges related to temporal effects of carbon accounting, geographical differences, such as ecosystem types, soil characteristics, tree species, land management practices and climate conditions. Addressing these gaps requires the development of a more dynamic, region-specific, and comprehensive methodology. This is especially important when considering bio-based building materials, which are typically wood or plant-based due to their capacity to function as carbon sinks. However, unsustainable land use changes can result in significant environmental impacts, such as increased greenhouse gas (GHG) emissions and loss of biodiversity and therefore, incorporating LULUC into environmental assessments is crucial for providing a more accurate and holistic understanding of the sustainability of bio-based materials in the construction sector (Hansen et al., 2024).

Circular and cascading flows

Further methodological gaps include the consideration of circular and cascading flows in the bioeconomy across the construction value chain, and their consideration in the LCSA framework. Indeed, aside from the temporal implications for e.g., carbon sequestration, the cascading of bio-based materials over multiple life cycles call for the EoL allocation of impacts between successive products. To this end, Luthin et al. (2023) propose to integrate a circularity assessment into the LCSA framework, and to include the quality of the material in the FU in addition to the quantified functionality of the material and projected lifespan, in order to account for its circularity in LCSA (i.e., since the future reusability or recyclability will depend on the material quality).

Cross-industry cooperation is necessary to ensure design for combined manufacturing assembly and disassembly (e.g., modular elements made of massive wood), as well as collaborative relationship-building across supply chains such as networks for waste management, could be developed along value chains for cellulose-based fibres (Aggestam and Giurca, 2022). As highlighted in T1.2, which focused on the hotspot analysis of the most impactful industrial processes for the five bio-based sectors, the forestry, woodworking and construction sectors are intrinsically connected since a large share of bio-based products used in construction are made from wood. Therefore wood-cascading approaches need to be developed by incorporating the wood-based waste generated in subsectors like construction (Linser et al., 2022).

Generally, construction waste can be reused or recycled efficiently at EoL if deconstruction operations are planned ahead and integrated into the value chain. Existent standardization for construction works (EN 15804+A2) includes several indicators used to describe resource use and environmental information based on processes' Life Cycle Inventories (LCI) and describe output flows for each life cycle module that can be further developed to integrate circular economy methodologies. These include the use of secondary material and accounting for net use of freshwater in closed-loop processes (e.g., cooling systems and reintegration of water losses) and power generation which need to be declared, in addition to transparent information regarding geographical and temporal specifications, type of water resource and quality standards. The description of components for recycling and re-use also needs to be detailed and declared when performing an EPD for construction products.

In 2020 the construction industry accounted for 37% share of the total European waste production (Eurostat, 2023), which emphasises the importance of waste management data accessibility to develop and implement circular economy and cascading approaches for the construction sector. Waste management is a highly complex practice due to the mixed composition of waste streams with materials from different life spans, and the difficulties in its separation and classification. For this reason, collecting and analysing data for the development of accurate and highly granular data sources regarding waste disposal and sorting is a key issue (Guo and Huang, 2019). This task is more complex when trying to consider only its bio-based dimension. Several approaches have been proposed including material flow analysis in combination with LCA to calculate embodied carbon and track material flows at a broader level over time. For instance, integrating geographical information systems (GIS) has been further explored for estimating building materials part of in-use stocks, as to detect spatiotemporal patterns and predict future material flows of individual buildings. However, this analysis has only allowed to assess volumetric information of building material stocks and not the precise classification of future waste (Guo and Huang, 2019).

Air quality and health impacts

The construction sector is closely linked to the quality of indoor air and the associated health impacts. Indoor health impacts may be relevant during production or renovation stages of buildings, often related to fugitive dust and/or volatile chemicals contained in various products (adhesives, paints, etc.), affecting air quality that can have negative impacts on the workers' respiratory health. Dust mitigation strategies need to be implemented in order to meet environmental regulations. During the use phase, contaminants may still be emitted at a slower pace, leading to low yet damaging concentrations due to the important length of the exposure of inhabitants. In addition, monitoring and controlling air quality is typically more challenging depending on the nature of the building. Indeed, unlike industrial buildings where emissions can be attributed to particular processes and their sources can be easily detected, residential and commercial buildings different air pollutants might be present in low concentrations but be difficult to identify due to the diverse activity patterns of the occupants and even the distinct locations where buildings are located (Paleologos et al., 2021). Furthermore, poor window ventilation and/or poor maintenance may lead to contamination of filters and ducts, and, together with humidity, to mould growth. Appropriate health and safety conditions for workers and the use of less harmful (possibly bio-) materials could diminish the impacts related to indoor air quality. Yet, the LCSA for different mitigation strategies is an underdeveloped field that still accounts for few developments (Raymond et al., 2021).

Within the European context, a harmonized and specific regulatory framework on the quality of indoor air is still lacking and requirements such as minimum air ventilation, limitation of pollutants and airtightness need to be urgently included in legislation frameworks, particularly with regard to buildings such as schools and healthcare where permanent workers and vulnerable people are exposed to indoor air for long periods of time. The World

Health Organization (WHO) has developed guidelines for indoor air quality (IAQ) considering some substances (benzene, nitrogen dioxide, polycyclic aromatic hydrocarbons, naphthalene, carbon monoxide, radon, trichloroethylene and tetrachloroethylene), and carcinogenic pollutants but no correlation is done with risks related to exposure to humidity and biological agents (Settimo et al., 2020). The European Union has also built several regulations including the 305/2011 for marketing of construction products, ISO 16000-Indoor air quality and (CEN/TS)16516: construction products-determination of emission into indoor air which is applicable to all kinds of facilities apart from those dedicated exclusively to industrial and agricultural activities, meaning the exclusion of the production life cycle stage of the construction sector (Settimo et al., 2020).

S-LCA and LCC methodological gaps

Standardization for LCC in the construction sector includes the ISO15686-5:2017 with an equivalent goal and scope to the environmental approach. However, no comparable impact assessment phase exists since the life cycle inventory only addresses currency as the unit of measurement and no further characterisation of results is required. The social dimension of LCSA is currently the most difficult to incorporate, and the state of the art mostly focuses on a particular life cycle stage and stakeholder, thus not accounting for supply chain interconnections. Studies focusing on social impacts for the use or production phase such as visual, thermal and acoustic comfort and indoor quality effects are only related to the consumer as the stakeholder (Backes et al., 2021). This remains a critical methodological gap because, as reported in T1.2—which focused on the hotspot analysis of the most impactful industrial processes for the five bio-based sectors—the stakeholder groups presenting the biggest social challenges, according to the survey approach, are employees within the value chain, followed by local communities, supply chain actors, and, finally, consumers. Numerous subcategories are recommended by (Backes et al., 2021) for the social dimension including public commitments to sustainability issues due to the extensive lifetime of buildings, including recycling, circularity and renovation of old buildings, development of innovative building materials and EoL responsibility and transparency. Furthermore, crucial social aspects when it comes to the inclusion of circularity in LCSA are job losses due to switch from a linear economy (society category), training and education for employees (worker category), and social acceptance (local community and consumer categories), among others (Luthin et al., 2023).

Within the construction sector, materials are rarely used individually and are instead combined to ensure high performance in the final product of the building. Therefore, the selection of the Functional Unit (FU) and underlying justification is crucial to establishing a coherent LCSA sectorised framework that takes into consideration the different impacts the same product can have, depending on the function under analysis. In particular, applying a FU is a bigger challenge in the social dimension mainly related to the difficulty of selecting quantitative indicators that cover entirely the construction supply chain (Ayassamy and Pellerin, 2023). Ayassamy and Pellerin (2023) reviewed 19 articles on how the social dimension has been addressed in literature for the construction sector, identifying a variety of FUs and system boundaries used by different authors. This ranged from weight specifications to area or cost-related criteria, as well as best and worst-case scenarios, with the FU often reflecting the company's behaviour rather than the product’s function. This approach contrasts significantly with the FU used in environmental assessments (Backes et al., 2021).

3.1.2 Discussions with industrial partner and other companies in the construction sector

Six stakeholders in the building and construction sector and a university with a research field in applied sciences responded to the questionnaire for this report. Among the stakeholders, we can list one independent LCA expert, one environmental consultancy specialized in LCA of construction materials, three producers of insulation materials, and one manufacturer of biobased materials for the building sector. The company's size ranged from 1 to more than 50 employees, and the individuals contacted were a task leader in LCA, three LCA experts, an engineering head of application, a product quality and certification manager, and a director. All of them are performing life cycle analysis, mainly for product development and EPDs, and most of them are currently only assessing the environmental dimension (i.e., LCA) in their current roles. When asked about the main gaps in the methodologies (LCA/LCC/S-LCA), the interviewed stakeholders mentioned the fact that temporary and permanent biogenic carbon storage and delayed emissions in EU LCA standards and legislations are not recognised. Also, the lack of agreement between the LCA world and politicians on methodologies for carbon sequestration and release causing a lack of standardized LCA methodologies on temporary or permanent carbon management.

The interviewed stakeholders mentioned that EoL scenarios are not fixed and change depending on the country and the verifier, for instance recycling may be accepted in some countries as future scenario and in some other only current EoL scenario is accepted (e.g., incineration).

Moreover, they state that datasets for bio-based materials are not easy to find or are outdated. Lastly, they identified the extensive list of labels existing in the construction sector which results in additional administration efforts, extra costs, and only making the product from bureaucratic instead of improving it.

They also mentioned that for product technical aspects, certifications are used for market development rather than for sustainability aspects and that a lack of harmonization exists among all existing labels for the construction sector.

Regarding S-LCA and LCC one said that the methodologies are not implemented yet to the projects, another mentioned that social indicators are not well developed, and the others did not mention gaps for those methods since they are not being mainstreamed at the moment.

Likewise, one of the LCA experts highlighted that while it is widely accepted by practitioners that allowing the communication of impacts from Guarantees of Origin (GO)-based energy products serves as a positive incentive to support investments in these production technologies, it is also vital to consider whether Environmental Product Declarations (EPDs) and LCAs are primarily documentation of actual impacts or tools designed to create incentives for industry investments and optimisations and that this distinction is critical for developing accurate, impact-driven LCSA frameworks for bio-based construction products.

Regarding which impacts categories are not well developed and how they could be improved, most respondents highlighted that Biodiversity is not reflected in the indicators used and do not reflect differences between agricultural activities like monoculture versus permaculture, which can be important for bio-based construction products. The same was referred regarding Land use change as they state that the indicator is not developed enough and does not reflect soil challenges. Harmonized data and approaches of calculation would be needed for those indicators. Moreover, they emphasized that carbon sequestration is not well developed in current LCAs standards.

For EPDs, they declare that indicators like Biodiversity and Toxicity indicators are misunderstood and generate confusion when getting the results tables of EPDs and that clarification at different levels would be needed. Finally, they say that circularity methodology and indicators would be relevant but that it is not currently targeted in EPDs. Finally, as a solution, two of the respondents said that development of circularity indicators and dynamic LCA methodologies would allow more regular update of assessments for technological advancements.

When asked about problems during data collection and other problems during assessments, most interviewed stakeholders state that there is a lack of data availability for several products in the datasets, including chemicals with high sensibility in their synthesis, minerals additives and glue/paints, making it necessary to rely on proxies or to conduct literature review which is very time consuming especially as most manufacturers do not give details of synthesis. To solve this problem, one of the experts mentioned using the Agribalyse database to collect specific data for agricultural products. Adding to this problem are the marginal differences between old and new data from mainstream databases making the impacts change when using a version or another.

Regarding other problems with the assessment, one of the experts said that while some datasets are region specific, the midpoints indicators do not reflect local environmental conditions, such as freshwater eutrophication which can only occur if there is freshwater available in the region for instance. Another problem highlighted is the lack of harmonization between methods or software as for instance, different systems in the Netherlands have extra requirements, making it difficult to convince companies to make LCAs with the Dutch standards as SimaPro is required to be used but several companies provide models in LCA for experts (GaBi). However, harmonization between methods and software is necessary since a vast quantity of building materials are imported from other countries.

Finally, when asked if they use different methods than LCA for sustainability assessment and the gaps associated, one mentioned using circularity assessment in multiple forms and noticing a lack of correlation between LCA and the planetary boundaries. Another one mentioned using EN15804, Dutch standards and Nature Plus method from Germany which focus on health-related aspects. Concerning S-LCA, one respondent declared using an internal framework developed within the company, a socio-economic assessment for comparison of biobased versus non-biobased materials for job creation during manufacturing and installation steps and consideration of local products.

3.1.3 Key levers to improve sustainability assessment methodologies in the construction sector

Based on the insights gathered during the interviews, it is evident that while environmental LCA is commonly used in the construction sector, LCC and S-LCA are rarely integrated. Moreover, the following conclusions emerge regarding how to address the identified gaps:

1. **Enhancing the availability of high-quality data for bio-based construction materials in LCA databases.** Improving the availability of high-quality data for bio-based construction materials in LCA databases is crucial for accurate evaluations. As highlighted in Calimero's T1.2—which focused on the hotspot analysis of the most impactful industrial processes for the five bio-based sectors—, many materials, including glues and paints, are either missing or outdated in current mainstream databases. Additionally, several bio-based insulation products are absent, such as those made from hemp, straw, bamboo, flax, sheep wool, reed, algae, agro-waste, cotton waste, and leather scraps. Current LCA databases often rely on traditional construction methods primarily utilizing concrete and steel, thereby neglecting innovative wood structures. By incorporating timber-based materials and modern construction techniques, we can better reflect the potential environmental impacts of bio-based alternatives compared to conventional mineral and metal options. With enhanced data quality and availability, decision-makers can ensure that comparisons between bio-based and fossil-based materials are grounded in reliable information, leading to more informed and sustainable choices.

2. **Integration of circularity indicators into the LCSA framework** is essential for improving sustainability assessments in the construction sector since many construction materials reaching the EoL stage retain the potential for reuse or recycling in other life cycles. Key challenges include determining how to allocate the environmental impacts of these materials across multiple cascading cycles and incorporating quality parameters, as the future reusability and recyclability of materials depend on their condition at the EoL stage. Establishing standardized circularity indicators will provide clearer guidelines

for assessing and promoting material recovery and reuse in line with LCSA methodologies.

3. **Implementation of dynamic LCA models for holistic calculations of sequestration and uptake of Biogenic Carbon emissions over time.** Several static methods are currently used to account for biogenic carbon, depending on the standardized guidelines being followed (e.g., 0/0, -1/+1, -1/+1*). However, all of these approaches fail to capture the dynamic nature of carbon storage throughout the lifecycle of bio-based construction materials or consider long-term carbon storage which is essential for the assessment of materials used in the construction sector, where carbon may remain sequestered for extended periods of time.

4. **Improvement of the LULUC indicator and development of a standardized methodology to incorporate indirect Land Use Change (iLUC).** The effects land use management have in carbon sequestration remain poorly quantified. By including iLUC it would be possible to account land-use shifts outside the immediate boundaries of production, capturing broader ecosystem impacts such as deforestation or biodiversity loss caused by land displacement. This would provide a more comprehensive sustainability assessment of bio-based construction materials and enhance transparency and comparability across construction projects.

5. **Development of Comprehensive and Dynamic Indicators for Ecosystem Services and Biodiversity:** Feedback from LCA experts working with bio-based construction materials emphasizes the urgent need for more robust indicators that capture ecosystem services such as the differences between monoculture versus permaculture, account for spatial and temporal variability—given that ecosystem services are highly location-specific and dynamic over time—and include indirect and long-term impacts, such as habitat fragmentation leading to biodiversity loss or soil degradation affecting agricultural productivity.

6. **Development of Consistent and Standardized Guidelines for S-LCAs.** The current state of S-LCA primarily focuses on specific life cycle stages and individual stakeholders, often overlooking the interconnectedness within supply chains. To develop standardized S-LCA methods effectively, several key aspects must be addressed:

   - **Functional Unit Selection:** Construction materials are rarely used individually; they are typically combined to form the final product of a building. This complicates the assessment, as the impacts of the same material can vary significantly depending on the function under analysis.

   - **Temporal Variability in Material Lifecycles:** Many construction materials have long lifespans, making it challenging to trace and account for social impacts at specific stages or locations throughout their lifecycle.

   - **Inclusion of Circularity and EoL Scenarios:** There is currently limited guidance in S-LCA methodologies for assessing social impacts associated with circularity—such as recycling or repurposing materials—and EoL processes in the construction sector. This gap includes evaluating the social implications for workers and communities involved in activities like demolition, recycling, or waste disposal.

7. **Clarification and improvement of Eco-toxicity and Human-toxicity impact categories across construction products complete lifecycle.** These impact categories are often poorly understood, leading to confusion between toxicity during production and the potential impacts during the use phase. This confusion is particularly pronounced when assessing agricultural activities and their associated

products, where the distinction between agricultural inputs (such as pesticides) and their effects on human health and ecosystems must be clearly delineated. To address these challenges, a comprehensive characterization of chemicals (paints, glue, fire retardants, adhesives, coatings) throughout the construction value chain is necessary. Developing dynamic characterization models will enhance our understanding of how the environmental and health impacts of certain exposure to chemicals change over time. Additionally, ensuring stakeholder engagement—including researchers, industry professionals, and policymakers—is essential for creating toxicity models that accurately reflect real-world scenarios and address community concerns.

3.1.4 Discussions on further work needed based on results

Based on the obtained results from the presented literature review and the conducted interviews, the following suggestions are given to improve the industrial case study of cellulose loose-fill insulation developed in the CALIMERO project for the construction sector:

1. Several impact categories—such as biodiversity, ecosystem services, and chemical toxicity (both eco-toxicity and human toxicity)— were recognized both in the literature and through the expert interviews as highly relevant to the sector. However, these categories are currently underdeveloped within PEF methodologies. Therefore, given that T3.1 is dedicated to developing robust and scientifically sound methodologies for assessing impacts on biodiversity, ecosystem services (ES), and new characterization factors for Eco and Human -toxicity of chemicals frequently used in bio-based industries, it is recommended to incorporate these advancements into the case study. Doing so would enable a more comprehensive and holistic environmental analysis, addressing key impact areas that are currently underrepresented in standard assessments and enhancing the study's relevance for real-world applications.

2. The baseline loose-fill cellulose insulation case study developed in T2.2—focused on defining case studies for the target bio-based sectors— primarily considers as EoL options incineration with energy recovery and landfilling, based on the shares provided by the PEF Annex C and following the Circular Footprint Formula (CFF). However, there is significant potential to recycle cellulose fibres in innovative ways: they can be repurposed as stabilizing agents in asphalt, used in the production of Solid Recovered Fuels (SRF), or even converted into plant fertilizers if additive-impregnated fibres are incorporated. Additionally, specially developed machinery allows for the direct reuse of the insulation up to 3-4 times or facilitates its reintegration into the production line as recycled insulation material. An approach emphasizing the critical pathway for incorporating circularity indicators into the LCSA framework for assessment of bio-based materials, will be further developed in T3.2. Such advancements would not only benefit LCA practitioners but also create added value for industrial partners in the cellulose insulation sector.

3. Finally, the permanent storage of biogenic carbon needs to be recognised as first step. Additionally, temporal modelling of carbon flows has been identified in both the literature and expert interviews as a key challenge for comprehensive LCSA methodologies. The baseline cellulose insulation case study could be refined by accounting for the time-based retention of carbon sequestered in cellulose fibres during the product's lifetime. This approach would provide a more accurate climate impact assessment, reflecting the benefits of using bio-based insulation over fossil-based alternatives. This innovative method for evaluating the carbon footprint will be further developed in T3.3—focused on improving the lifecycle carbon footprint for the target bio-based sectors—aligning with a more holistic understanding of carbon impacts in LCSA methodologies.

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3.2 Woodworking sector

3.2.1 Literature review of methodological gaps in the woodworking sector

LCA methodological gaps

Ecosystem services

Wood pastures have been a recurring object of study in the analysis of ecosystem services, which constitute complex socio-ecological systems as a result of long-term interactions between society and the surrounding landscape (Torralba et al., 2018). In the work carried out in the Spanish context, a series of surveys were carried out with a range of stakeholders, which revealed significant differences between sectors and levels of governance. For example, provisioning services were mentioned by the local population and the private and public sectors, while the civil sector and the regional population emphasized regulating and supporting services, such as biodiversity or climate regulation. However, all respondents considered cultural services (e.g., traditional knowledge, cultural landscape or heritage values) as the most important category, although they are often overlooked in ES valuation procedures based on biophysical or economic approaches (Garrido et al., 2017a). In addition, a similar study was conducted in the Swedish wood pastures, where again cultural ES were the most highlighted aspect (Garrido et al., 2017b).

Biodiversity

The woodworking sector has a significant impact on biodiversity. Depending on the type and origin of the wood, the methods and technologies used, and the management and mitigation measures implemented, the impacts can be either beneficial or detrimental to the environment. Positive impacts can include reducing the demand for fossil resources or promoting sustainable forest management certifications that prioritize the well-being of ecosystems and biodiversity. Conversely, negative impacts may include deforestation, the introduction of invasive species, or noise and air pollution from woodworking factories that indirectly contribute to climate change (Schröder et al., 2019). Therefore, there is a need to develop new indicators that accurately describe biodiversity loss associated with forestry activities. Impacts on biodiversity can be represented as intermediate impact categories, while biodiversity as a whole is categorized as an endpoint, represented by ecosystem health. In assessing biodiversity in the woodworking sector, the use of land use as a proxy indicator is a popular approach. However, it focuses primarily on the number of species in an ecosystem, which is not the only determinant for measuring changes in biodiversity. On the other hand, other authors have adapted by quantifying genetic diversity or the presence of invasive species in a given area (May et al., 2017).

Carbon footprint

Naturally, trees can sequester carbon (depending on forest management practices) and derived wood products store this carbon over time. Consequently, the inclusion of the temporal aspect in the LCA methodology can lead to a large variation in the results obtained, especially regarding the global warming potential (GWP) in those sectors related to climate change mitigation. An example of this is wood-based products used in construction, which can be a climate-friendly option compared to other construction materials, as they can play the role of temporal carbon sinks. However, by default, traditional LCA method (i.e., "static" LCA) do not take into account the atmospheric dynamics of carbon storage and release, nor the (cumulative) heat-trapping capacity of GHG emissions over time, resulting in a "static" potential GWP impact. As a result, several studies have been carried out with the aim of demonstrating the differences between the static and dynamic approaches of these two LCA methods: "dynamic" LCA, taking into account the temporal aspect, and "static" or traditional LCA. One of them is the work of Wang et al. (2022), which shows that ignoring the time factor leads to an underestimation of climate change impacts and an overestimation of mitigation potentials for a wood-based panel case study in a Chinese context. Furthermore, a "static" consequential LCA shows an overestimation of the long-term cumulative impact on climate change compared to the "dynamic" alternative when modelling three different harvesting and growing scenarios along with several EoL strategies and considering material substitution in wood-based products used in the construction sector (Cordier et al., 2022).

Indoor health impacts

Indoor health impacts in the woodworking industry include several factors. Workers are exposed to wood dust and volatile compounds released from chemicals in adhesives, solvents or paints, resulting in adverse effects such as toxicity and respiratory diseases (Araújo-Vila et al., 2022). In this regard, the Directive 2019/983/EU establishes occupational exposure limit values for hardwood dust and formaldehyde (European Union, 2019), while the European Agency for Safety and Health at Work highlights complying with the occupational exposure limit for formaldehyde in the wood industries (European Panel Federation, 2018). In addition, there are ergonomic risks associated with operating hazardous machinery that can produce vibrations and high noise levels (Turan and Yildiz, 2021). Regarding methodologies for assessing indoor health impacts in the wood sector, there is no standardized or harmonized approach. However, a voluntary approach was launched by the European Commission in 2022, the Safe and Sustainable by Design (SSbD) framework, for guiding the innovation process for chemicals and materials through a (re-)design and assessment stages. The first stage involves applying guiding principles to steer the development process, while the second one comprises hazard assessment, worker exposure during production, exposure during use and LCA (Caldeira et al., 2022). However, the SSbD framework is not specifically designed for the woodworking sector so it does not cover particular aspects such as wood dust.

Circularity

Regarding the circular economy concept, two different case studies were evaluated by Husgafvel et al. (2018) through questionnaires and interviews: (i) one based on the identification of the sustainability-driven competitive advantage within the forest and bio-product industry, and (ii) the other focused on the identification of potential opportunities and barriers for cascading recovered solid wood. These were carried out in a Finnish context and in both of them the LCA methodology was highlighted as a key pillar for the transition phase of sustainable development in the woodworking sector. In addition, it was identified the need for new approaches accompanied by the training of personnel in knowledge, skills and competences related to sustainability. In this line, an appropriate modeling of woodworking manufacturing processes could be a helpful way to compare different recycling alternatives, as well as to avoid burden shifting issues when considering a holistic view of the different life cycle stages.

Criticality

A literature review of methods for determining raw material criticality highlights the limitations of high-quality data in terms of uncertainty and representativeness and identifies wood as one of the raw materials for which few data are available. In addition, paving the way for standardized quality criticality assessments requires consensus on the definition of objectives and scope, as well as the selection of appropriate indicators and aggregation methods, since contextual factors and choices have been shown to be two key determinants of criticality assessment results (Schrijvers et al., 2020). This lack of data for biotic renewable resources such as wood may be due in part to the fact that the assessment of supply risk is more focused on mineral resources. However, a lack of sustainable management of wood can lead to supply shortages. In this line, a criticality assessment framework has been developed to be applied to a construction wood product system, including a number of different perturbing factors (e.g., fires or trade barriers) (Ioannidou et al., 2019).

S-LCA methodological gaps

Numerous challenges within S-LCA related to the woodworking sector are fixed by a predominant emphasis on foreground activities, leaving background processes with comparatively less detailed analysis. As described by Siebert et al. (2018), environmental LCA assessment benefits from simpler cause-effect chains, while S-LCA faces difficulties in correlating different wood production activities with their corresponding social impacts. This complexity poses problems in the selection of appropriate indicators for a comprehensive assessment. As a result, the lack of standardized indicators has led to a proliferation of social metrics in the literature, sometimes without clear guidance or justification for their use. Similarly, the lack of context-specific S-LCA methodologies is a notable challenge. The socio-economic aspects considered important for S-LCA depend on the regional context, highlighting the urgent need for tailored methodologies that skillfully take into account the unique characteristics of each study area (Roberts et al., 2022). These challenges highlight the inherent complexity of assessing the social dimension of wood production systems, and underscore the essential need for continued development and standardization.

3.2.2 Discussions with industrial partner and other companies in the construction sector

Four stakeholders in the woodworking sector responded to the questionnaire for this report. These were two companies providing wood-based products used in furniture, interior design and construction, as well as two environmental consultancies routinely working with companies in the woodworking sector for the evaluation of the environmental impacts of their products. The companies ranged in size from less than 10 employees to more than 1,000 employees, and the individuals contacted were an R&D Manager working on circular economy issues, a Technical Director, an EPD auditor and a Quality and Innovation Manager. All of them are performing life cycle analysis, but most of them only for the environmental dimension (i.e., LCA) in their current roles. In fact, only a few environmental indicators are being addressed, such as carbon footprint (including sometimes the carbon retained in the wood products) or water footprint, performing comparisons, EPDs or environmental self-declarations.

When asked about the main gaps in these methodologies (LCA/LCC/S-LCA), the interviewed stakeholders mentioned a lack of high-quality, comprehensive data, as well as standardized methodologies, this leading to variable results and interpretations that make difficult the comparison among studies. In addition to this, the verification process of the EPDs was criticized by its lack of rigor, obtaining anomalous results, thus generating mistrust and affecting competitiveness between companies. In LCA specifically, the existence of only few tailored databases related to specific tree species was also highlighted, as well as a lack of a reliable and clear methodology for estimating the biogenic carbon dioxide (CO_2) contained in products, especially in the wood ones. In this regard, PEF methodology does not take into account the carbon removal as a credit for plants during the photosynthesis process, as well as the effect of climate change mitigation when the carbon is stored for extended periods for long-lasting applications (e.g., construction), producing a no-differentiation effect when it is compared to their fossil-based counterparts. Regarding data gathering, it was defined as a very time-demanding activity, finding difficulties for collecting good-quality information for traceability and out-of-date issues, thus forcing to make use of secondary data. Putting the focus on S-LCA, some lacks emerge, such as the need for methodological standardization, regional contextualization or difficulties when integrating to environmental or economic assessments due to commonly-used indicators of quantitative nature. Particularly, one of the interviewees argued that this kind of methodologies should not be influenced by external factors such as political thoughts. Lastly, in LCC a lack of economic experience was identified, as well as a need of a greater development and unification of methodologies.

Regarding the goodness of existing impact categories and how could the assessment of these impact categories be improved, again, most respondents highlighted climate change and specifically biogenic carbon. In this regard, some solutions were proposed, including taking into consideration the uptake of biogenic carbon by plants, implementing a cradle-to-grave approach, improving the accounting for mixed feedstock scenarios where biomass is blended with fossil feedstock and ensuring transparency and standardization across the different sectors. On the other hand, it was also claimed that the PEF weighting factors are highly biased, exaggerating the importance of climate change relative to the other impact categories, with no technical or scientific basis for this bias. It was also highlighted that the impact of water use, particularly in regions where water scarcity is a concern, is not always adequately addressed due to the complexity of water footprint methodologies.

When asked about specific problems related to data collection during assessments, the main issue arising was the lack of data availability and traceability when working with small corporations, such as sawmills and logging companies. In many cases, these small companies don't have specific software that ensures traceability or don't record the required data with enough periodicity, which in many cases makes necessary to use out-of-date information. In addition to this, the difficulty in obtaining accurate data for climate change impacts was specifically pointed out due to the fact that most suppliers don't calculate their own products' footprint. Finally, the origin and traceability of wood, apart from the end use of wood-based products were also raised as problematic, especially in view of the long lifetime of such construction products.

3.2.3 Key levers to improve sustainability assessment methodologies in the woodworking sector

Based on the insights provided during the interviews, it is noticeable that, while environmental LCA is relatively applied in the woodworking sector, LCC and S-LCA are rarely considered. Besides, the following conclusions arise when it is referred to improve the gaps identified:

- Given the widely used of the carbon footprint as a stand-alone environmental indicator, it is necessary to establish a reliable and clear methodology for estimating the biogenic carbon contained in products, especially for wood products. In this regard, it is of paramount importance:
  - Recognizing biogenic carbon uptake by crediting the CO_2 emissions absorbed by plants during photosynthesis. This can be achieved by adopting a -1/+1 approach, which accounts for the carbon uptake during the growth phase and the emissions at the EoL.
  - Implementing a comprehensive cradle-to-grave approach for ensuring that credits of biogenic carbon sequestration are considered throughout the product's life cycle.
  - Encouraging the use of bio-based materials in long-lasting applications (e.g., wood employed as material for construction purposes). This would help sequester carbon for extended periods and promote a circular economy.
  - Improving the accounting for mixed feedstock scenarios where biomass is blended with fossil feedstock. In fact, this would highlight a GHG reduction when using bio-based materials.
  - Ensuring that the methodology is transparent and standardized across different sectors. This would help in comparing the environmental impacts of bio-based and fossil-based products in a more accurate way.
  - Promotion of the carbon footprint calculation among small players of the woodworking sector, as well as suppliers from adjacent sectors, is crucial to ensure data availability.
- It is of paramount importance that LCA databases are expanded and developed with rigorous technical and scientific criteria.

- Collaboration between LCA specialists and companies' technicians is crucial, making sure that all the doubts are answered via consultations.
- Conducting double-checks procedures for the life cycle inventories through estimations of ratios or indices in order to detect anomalous values is also of great importance, as well as performing a final validation step once the LCA has been conducted with the help of the industrial experts.
- Comprehensive and international recognized methodological procedures for the S-LCA and LCC are needed, enabling fair comparability between products/companies.

3.2.4 Discussions on further work needed based on results

Based on the high variety of methodological gaps which are related when evaluating the woodworking sector by applying sustainability assessment methodologies, it was decided to narrow the scope to the specific industrial processes addressed in the CALIMERO project (i.e., (i) Laminated Strand Lumber production and (ii) Steam production from residual biomass). To do this, tailored improvements or solutions of the LCSA methodology are proposed in view of their particularities and the main hotspots identified.

The impact of climate change, in terms of GHG emissions, has emerged as a point of concern for both the forestry activity and the manufacturing process. As far as the forestry activity is concerned, it was carried out according to specific practices (leaving the stumps and planting the next generation right next to them), which guarantee compliance with sustainable forest management according to the PEFC (Program for Endorsement of Forest Certification) label in a specific time frame (14-year rotation). However, these practices were not taken into account in the LCSA, so a better accounting of the carbon footprint of poplar forestry is needed. On the other hand, focusing on the manufacturing of wood panels, there is no monitoring of the emissions associated with the production processes. As a result, their contribution to climate change has been uncovered. Based on these findings, the refinement and expansion of the GHG emissions assessment can be addressed through two initiatives:

- Consideration of the temporal dimension. In this sense, the carbon footprint of the case studies can be modified by taking into consideration a dynamic perspective. In this way, the temporal dimension is considered and thus the time of retention of the carbon sequestered naturally by the wood, as well as the timespan of the wood panels. This will produce a recalculation and refinement in relation to the global warming potentials previously estimated. This novel procedure to assess the carbon footprint will be addressed in T3.3—which aims to improve LCI calculation of GHG by incorporating temporal dimension.
- Simulation of emissions related to the production of wood panels. For the cases studied in the CALIMERO project, the main emission point that is not yet monitored is the one coming from the steam production of the boiler. Its accounting then opens the door to reveal the true contribution of this key step in relation to the entire process in terms of climate change impact, and also promotes the application of mitigation strategies to reduce the carbon footprint. To do this, the emissions associated with steam production shall be modeled in T2.2, where simulation methods are applied to assess the sustainability improvements in the LCSA analysis for the representative bio-based case studies.

Likewise, the inclusion of additional impact categories will be proposed in order to broaden the scope of the environmental analysis. In this regard and according to the ecosystem services accounting, this will be studied from a regulating and supporting services perspective, but more precisely by the proposal of specific characterization factors of the biodiversity taking the land use of the forests that supply the raw material in the form of wood as reference. Impacts on biodiversity and ecosystem services will be tackled through a methodological improvement of the LCSA methodology in relation to T3.1, which focuses on developing previously missing characterization factors for LCSA.

In relation to the lack of consensus when evaluating the social dimension when following a life cycle perspective, a methodological procedure is proposed that considers the potential jobs created in the value chain of the production process. In addition, this is divided depending on if the job created is related to the bio-economy or not, apart from other key aspects such as the skill level (i.e., low, medium or high) or gender. Through this procedure, it is achieved that the social evaluation is aligned with one of the main objectives of the bioeconomy strategy integrated within the European Green Deal, which consists in the creation of bio-based employment. On the other hand, through the detailing of the types and characteristics of the jobs (skill level associated or gender involved) it is also made demand to other social issues of great importance in the Spanish timber sector such as generational replacement (lack of qualified personnel) and parity (gender gap).

As with the social dimension, circularity and criticality are also notable for the lack of consensus in their measurement. In the woodworking case study related to LSL manufactuting, the green wood used in the factory comes from the top parts of poplar trees, which are usually discarded because they are not of sufficient quality for plywood production. Therefore, the fact that this wood "waste" is used as a raw material for a carbon storing, high added value product (instead of for energy production) is not taken into account in the impact assessment. Therefore, to remedy this situation, circularity indicators and criticality aspects will be proposed in T3.2—whose objective is to integrate circular economy and criticality aspects into the LCSA framework. In this sense, the way in which the cascading of wood use can be taken into account for reuse or recycling will be evaluated, as well as the level of criticality of the type of wood used in the case study according to the socio-economic context of the area.

Lastly, emissions of human toxicants, both carcinogenic and non-carcinogenic, and particulate matter were also important issues in the LCSA. However, the plant does not currently have a monitoring procedure for these. In addition, specific substances from the adhesive used in the gluing process are not included in the recurring LCA databases such as Ecoinvent. Therefore, a two-step procedure has to be done in order to solve this safety worker issue. First, to run a simulation about what kind of substance and in which quantity are produced. Second, to which extent this can produce an impact through the inhalation of the chemicals by the workers. For the former, Aspen software is employed in T2.2, while for the later, tailored characterization factors are developed based on machine learning in T3.1.

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3.3 Pulp and paper sector

3.3.1 Literature review of methodological gaps in the pulp and paper sector

LCA methodological gaps

The following main methodological areas were identified as crucial for LCAs of paper and pulp products: Data selection and life cycle inventory, handling of multifunctionality, system boundaries, and impact assessment methods. In addition to this, methodological challenges related to s-LCAs are also described.

Data selection and life cycle inventory

The selection of appropriate data is of great importance for all LCAs. However, for pulp and paper industry, there are specific types of data that are important: Manda et al. (2012) write that the selection of source of electricity has a large influence on the end result of the study. They use the example of modelling the system so that the pulp mill uses energy generated internally from the black liquor and biomass, and that the remaining energy is used to cover part of the energy needed for an integrated paper mill. This can be compared to the assumption that the excess bioenergy will be used to generate power to the grid, and that the integrated paper mill uses electricity from the grid instead.

Handling multifunctionality

Sandin et al. (2016) identifies the handling of multifunctionality as a methodological challenge when assessing forest product system. This is because both the forestry and the subsequent processing of the materials generates several different products. Additionally, the waste handling at the EoL may also generate recyclable or reusable materials as well as heat and/or electricity. Results found by scholars such as Cherubini et al. (2011) and Sandin et al. (2015) state that results vary significantly depending on the allocation approach used in the assessment. Sandin et al. (2016) even states that the choice of method for handling multifunctionality in LCAs of biorefineries is to be considered a critical methodological choice. This statement is also supported by Hermansson et al. (2020) who assessed the influence different allocation approaches had on the resulting climate impact for lignin extracted from a Kraft pulp mill.

System boundaries

Manda et al. (2012) means that the inclusion of the disposal phase is important for paper products, as there are several options for paper’s EoL. This means that preferably, an LCA for paper should be cradle-to-grave.

Impact assessment methods

Sandin et al. (2016) writes that established LCI and life cycle impact assessment (LCIA) methods does not adequately address some environmental impacts of relevance for forestry and forest products. Examples of such environmental impact are climate change, biodiversity loss, disturbances to the water cycle as well as energy consumption. Likewise, as was highlighted for the woodworking sector, the modelling of carbon flows of forest product systems is a challenge (Sandin et al., 2016). This includes the spatial modelling of carbon flows (primarily related to forestry), but also temporal modelling of carbon flows. The latter is related to the timing of the carbon flows: the capturing of CO_2 in the forest and the emission of fossil and non-fossil GHG. Sandin et al. (2016) points out that this is problematic for two reasons; If using the GWP indicator over a 100-year time period (GWP_{100}), the 100-year time period is not being applied consistently. Secondly, the risk of passing critical tipping points in the climate system suggests that urgent impact mitigation is needed, and that the timing of the emissions matters.

S-LCA methodological gaps

Unlike LCA, S-LCA methodology has not been a widely used method so far, and its implementation on pulp and paper sector is very limited. Costa et al. (2022) assessed the Portuguese pulp and paper sector using input/output (IO) analysis and social hotspots database (SHDB). They pointed out the unavailability of consumers and children stakeholder categories, and the dominance of local community and worker related social themes compared to value chain actors and society related ones as methodological gaps related to analysis based on input-output databases. The lack of methods for assessing positive impacts is another gap defined by Costa et al. (2022).

LCC methodological gaps

Data uncertainty and incompleteness

A key gap in LCC for the pulp and paper industry is relevance to the availability and reliability of cost data across the lifecycle stages of products, particularly when evaluating costs for energy use, water consumption, and waste disposal. The sector faces variability in resource prices (e.g., water and energy), affecting long-term cost forecasting. There is often incomplete data regarding the environmental externalities with various production stages, making it difficult to integrate these costs into LCC assessments. This challenge is specifically highlighted in the context of both environmental and economic studies, where gaps in data collection from suppliers and partners along the supply chain are common in this sector.

Nieminen (2001) studied on merging economic considerations with environmental LCA to create a more comprehensive evaluation tool for the pulp and paper industry. It identifies challenges in incorporating full economic costs, including externalities and indirect costs, into LCA frameworks. The research highlights the need for improved data collection and methodological development to accurately assess both environmental impacts and economic viability, aiming for a more sustainable approach in the pulp and paper sector. She highlights several data-related challenges, particularly related to the availability and reliability of cost data. One major issue is the lack of detailed data on indirect costs. Indirect costs are often called overhead costs and they are those that are difficult to allocate to any product (if the company produces several products). She also mentions that indirect costs consist of costs that are not proportional to the volume of production, for example lighting, heating and cleaning. These kinds of costs could be managed by companies. Generally, the company has long experience of calculating these rates of indirect and direct costs. Moreover, data collection across different lifecycle stages (from raw material extraction to disposal) is often incomplete or inconsistent, leading to gaps in economic assessments. This incomplete data limits the accuracy of evaluating long-term economic impacts, particularly for costs that span beyond direct operations, such as EoL waste management or emissions abatement.

Inconsistent allocation of costs for by-products and waste

The pulp and paper industry produces significant quantities of by-products such as lignin and other biomass waste, which can be reused or sold. However, there is no clear consensus in LCC methodologies on how to allocate costs and revenues related to by-products, leading to inconsistencies in cost assessments. This gap could be especially important for industries which produce both paper and bio-based energy, where attributing costs proportionally can significantly impact the outcome of LCC analyses.

Pichler (2019) studied on determining the key factors that influence the selection of cost allocation methods in biorefineries. Specifically, it examines the allocation of costs between by-products, such as lignin and fiber fines, which are generated during the pulping process in paper production. Using the analytic hierarchy process (AHP), a structured decision-making method, the study identifies and ranks the factors that affect the choice of allocation methods in biorefineries. These allocation methods are important because they determine how costs are distributed between primary products and by-products, impacting the economic assessment of production processes. The lack of a standardized approach for allocating costs in biorefineries presents a challenge for comparisons between different processes or companies. This leads to inconsistencies in LCA and cost assessments, complicating efforts to improve sustainability. Different allocation methods (e.g., mass-based, energy-based, or economic value-based) can also lead to significantly different outcomes, affecting the perceived profitability and environmental sustainability of the biorefinery processes. The selection of an appropriate allocation method often involves subjective judgment, and there is no universally accepted standard. The preferences of decision-makers and stakeholders play a critical role, making it difficult to achieve consensus across industries and regions.

3.3.2 Discussions with industrial partner and other companies in the pulp and paper sector

In total, representatives from three organisations were interviewed. These included paper product producers, research institutes working with LCA or forestry management. The actors ranged from very large (>35 000 employees) to smaller (just below 150 employees). While the interviewees themselves always did not perform LCSA, it was in all cases done within their organisations. Assessment methods for other dimensions such as LCC and S-LCA were rarely used. One reason for not using these were that the stakeholder had access to other tools and systems to detect these kinds of problems and work with improvements.

When asked about the main methodological challenges (LCA/LCC/S-LCA), the stakeholders generally mentioned the lack of available good data. A general comment given was that the results of an LCA is very dependent on the availability and quality of data. One stakeholder specifically mentions the lack of data and characterization factors as the main challenges, and that to do a good LCA we need both. Practical examples mentioned is lack of appropriate inventory data related to biogenic carbon, water use, and waste (especially for other regions than Europe). This is combination with lack of characterization factors for toxicity, land use, and water use makes the assessment challenging. A related aspect is the challenge to foresee the influence of changes, for example in raw material extraction as well as what products that are being produced. Finally, the use of sound allocation approaches in recycling was brought up by one stakeholder. The stakeholder concludes that all approaches include some sort of value choice which needs to be made aware of. Finally, one stakeholder brings up the variation of quality between impact categories as a methodological challenge. This makes the analysis of the most important results difficult when including more than one impact category.

When asked about the quality of available impact categories and how these could be improved, the stakeholders meaned that there is a need to develop the impact categories related to biodiversity and changes to ecosystem changes (as has been highlighted as challenges for the construction and woodworking sectors). A suggestion on how to improve these is to build the assessment on the conditions for improving biodiversity or ecosystem services: Has anything been done to increase these? Another suggestion from a stakeholder is to go further than midpoint level for these, or to only look at e.g., soil quality. Other impact categories needing more development being mentioned are toxicity, land use change and climate impact, biogenic. One suggestion to improve these is to collect more and better data by a large variety of people to develop better, publicly available, CFs.

When asked about specific problems related to data collection during assessments, one stakeholder gives outdated models as an example. Because of new management practices available models used to generate data, especially for the forestry sector, are getting out of date. This problem is also relevant to the

Assessment of pulp and paper products, as there is a large need for inventory data for biogenic flows as well as for other land use related parameters to make fair assessments. Another problem related to collecting data from the forestry is the challenge in selecting appropriate system boundaries. The system's complexity and the connection to the overall sector is challenging to handle: What happens in the forest, what happens in the raw material? And What happens in the end- product? Finally, the problem of lack of data within professional LCA databases as well as lack of data for specific regions are also highlighted. Another topic brought up by another stakeholder is the difference in data quality. A practical example mentioned that in old datasets for electricity use, a flow of chrome led to very high ecotoxic levels. Not having access to up-to-date background data can therefor lead to skewed conclusions.

3.3.3 Key levers to improve sustainability assessment methodologies in the pulp and paper sector

Based on the insights provided by the literature review and interviews, key sectorial levers to improve sustainability assessment of pulp and paper are identified:

- Develop methodologies for assessing changes to biodiversity and ecosystem changes
- Improve the assessment of climate impact from biogenic carbon, especially related to temporal flows, and to provide clear guidelines on how to account for these for pulp and paper products.
- Develop impact assessment methods S-LCAs
    - There is a lack of appropriate impact assessment methods to account for positive impacts from the pulp and paper sector, as well as impact categories related to the stakeholders consumer and children.
- Develop datasets and characterization factors for a wide range of regions
    - There is a large need for public reginal characterization factors
- Develop guidelines for modelling of energy use and generation in pulp mills and biorefineries
    - Results are highly influenced by if internal energy generation is generated and handled/used
- Develop guidelines for handling multi-output processes in LCAs of pulp and paper production
    - Forestry, pulp mills, and biorefineries often have multiple outputs. How these are handled and how the impacts of the system are allocated influences the outcome significantly. This is also applicable and important for better LCCs of pulp and paper
- Develop guidelines and increase awareness that handling of multifunctionality from recycling is based on, conscious or unconscious, value choices.

3.3.4 Discussions on further work needed based on results

Based on the results presented above, we suggest that the pulp and paper case studied are improved from two key perspectives:

1. The current tissue case study is cradle-to-gate. However, it should be developed to cradle-to-grave and include recycling of tissue paper. This would address and include the key levers of the handling of multifunctionality from recycling that was highlighted as a main challenge by one stakeholder. The main challenge is described to the methodological choice being connected to subjective value choices. This is not a solitary observation but has been highlighted by various scholars before (see for example Ekvall and Tillman (1997) and Frischknecht (2010)). This means that both the pulp and paper sector would benefit from addressing this, as well as the LCA community. Additionally, it would address the challenge identified in the literature review by Manda et al. (2012), who suggests that due to the varying options for paper product's EoL, cradle-to-grave assessments are preferred.

2. Assessing the handling of biogenic carbon accounting: While the methodology for this is rather well developed, the application and execution of it is seen as problematic. It has been pointed out that the current way biogenic carbon is handled in, e.g., PEF currently (characterization factor of 0, not accounting for biogenic sequestration) does not support decision making. Therefore, the CALIMERO project could test and assess how using the +1/-1 approach would function in the pulp and paper case study. Additionally, addressing the temporal modelling of carbon flows has in this study been highlighted as a challenge. Future work on pulp and paper assessments should focus on addressing both of these challenges related to assessing the climate impact.

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3.4 Textile sector

3.4.1 Literature review of methodological gaps in the textile sector

LCA methodological gaps

The use of LCA as a method for the assessment of textile garments environmental impacts has greatly increased in recent years especially in response to the textile sector's need to reduce its excessive environmental burden largely dominated by a linear production of short-lasting products contributing to an ever-increasing production and waste generation. A literature review has, however, highlighted that several knowledge and impact assessment gaps still hamper a comprehensive evaluation of the textile sector environmental impacts. Some novel environmental impacts are either not fully characterized due to data gaps or are still lacking a robust assessment method: Eco- and human toxicity impact assessment.

The textile industry is responsible for the consumption of large quantities of chemical products particularly during the wet treatment process and is responsible for 20% of wastewater pollution worldwide (de Olivera et al., 2021). Most of the impacts associated with the use of chemicals products in the textile manufacturing refer to the manufacturing and supply of those chemicals, and tend to exclude, due to lack of data, the impacts associated with the emissions of process effluents.

Similarly to findings in other sectors of the CALIMERO project, limitation in the assessment of toxicity (eco and human) impacts from the use of chemical products are due to the lack of transparency on the composition of the chemical products and the resulting degradation products. This level of transparency is necessary when modelling the fate, exposure levels and toxicity effects from the use of a chemical substance and which are required to calculate the characterisation factor (CF) for eco-toxicity and human toxicity impact assessment method. Unless the composition and degradation products of each chemical input is disclosed, the impacts associated with the release of those substances in the environment is overlooked (Roos et al., 2019).

Moreover, from a methodological perspective, the mainstream LCA methods do not consider the temporal dimension at which the emission in the receiving environmental compartment occurs, but it calculates the associated impacts for a mass of substance emitted as proportionally constant over an infinite time horizon and ignoring the non-linear distribution of an emitted mass of substance over time (Shimako et al., 2017). Shimako et al. (2017) argue that this approach can hide/dilute the potential impacts that occur at the emission period as all substances are considered in equilibrium in the environmental compartment. According to the authors, this approach overestimates and generalises the total toxicity impacts and suggest that a dynamic calculation approach should instead be employed to take into consideration the difference between non-persistent and persistent chemical substances (Shimako et al., 2017).

Land use impact assessment and water use

Land use impacts are associated with the extraction and supply of primary bio-based raw materials for textile manufacturing. Consistently with what has been presented in the pulp and paper, and woodworking sectors, current LCIA methods for land use impacts are not sufficiently developed to capture the importance of "locations of the operations" (Sandin et al., 2013). The strong dependency between the land use impacts and the location is according to Sandin and Roos (2019) important to factor in both at the inventory level and the impact assessment level, if differences in terms of biodiversity and soil quality impacts between alternative (more environmentally friendly) forestry/farming practices need to be captured, as the consequences of a given pressure in one area is not equivalent to any other area.

This limitation has been demonstrated in the work of Bos et al. (2020) where the authors showed the influence of site specific pedological, topographical and climatic conditions on land use impacts. To refine the assessment of land use impacts that are particularly pertinent to the evaluation of natural fibres production vs synthetic fibres, it is necessary to develop site specific CFs in particular for large production areas where the soil attributes may present variation at a much lower spatial scale; thus, avoiding overestimating the impacts of natural fibres production (Wiedemann et al., 2023). Additionally, land use impact assessment poorly defines the relationship that exist between land occupation (expressed as stocking rate) and sustainability, which contrary to other environmental flows, is not so direct. This impact assessment limitation negatively influence change to more sustainable low stocking rate practices (Wiedemann et al., 2023) and Wiedemann et al. (2020) calls to improve current inventory values to correctly model natural fibres production.

Regarding water use impacts, those are calculated based on the AWARE database, but Wiedemann et al. (2023) criticise that this database is based on irrigation data of 15 years ago and should be updated.

Microfibers release impact assessment limitations

Textile garments release fibres throughout their full life cycle. Quantity and type of fibres released depend on the textile material (natural vs synthetic) and composition (virgin vs recycled). Textile fibres are classified as micro (<5 mm) and nano (<100 nm) fibres and have been found in all environmental compartments (soil, water and air), with 35% of the microplastic pollution found in the oceans originated from textile garments (Pandit et al., 2020).

There is growing knowledge of the effects of micro and nano fibres, principally of synthetic origin, both in terms of ecological and human health effects (Henry et al., 2019). Despite the growing concerns with the effects of microplastic pollution, current LCA methods are not capable of characterising the effects of microfibers released in the environment from a given type of textile.

The main difficulty is to the define a credible mid-point indicator representative for the environmental effects from microplastic pollution. The limitation to this end, is to pinpoint the property of the microfibers that determine ecological and human health impacts. Different textile will shed different types of microfibers when washed. While natural materials fibres have been found to be completely degraded both in the environment and in organisms, synthetic ones are persistent and accumulate in the environment, ultimately increasing the exposure to animals and humans (Henry et al., 2019).

According to Henry et al. (2019), while a more robust indicator for ecological and human health impacts is developed, an interim mid-point indicator could be based on the mass or number of fibre loss per type of textile measured according to wash test, and that occurs during the garment use phase. Peano et al. (2020) also propose a complementary indicator to evaluate textile microplastic leakage.

LCA database limitations

Severe limitations exist also at the inventory building stage, with limited availability of representative fibres datasets, importantly for blended fabrics. Rossi et al. (2024) highlighted critical database gaps for fibres manufacturing processes both for plant based and synthetic based fibres. Moreover, Rossi et al. (2024) point out that lack of data on the composition of garment and textile products limits the modelling of an accurate textile product anatomy.

S-LCA methodological gaps

Socio-economic sustainability assessment is highly relevant for the textile and apparel sector given the negative social impacts often occurring in in their supply chain. Textile manufacturing is mainly concentrated in areas with poor working conditions and labour rights, making therefore the application of a social impact assessment highly relevant and much needed. On the other hand, the textile sector represents a driver of economic and employment creation in less developed countries, contributing to the fulfilment of the main objective of sustainable development of "prioritising the essential needs of the world's poor" (Hall, 2019). The inclusion of the social and economic impacts in the production of textile products becomes fundamental for a transparent and complete evaluation of textile products manufacturing impacts.

In a literature review conducted in 2015 on the application of S-LCA to the textile sector, Zamani et al. (2018) find no application of this methodology to the textile sector. Munõz-Torres et al. (2022) also show that the assessment of the social dimension is overall still underexplored in the textile sector with limited publications, and Martin and Herlaar (2021) refer to studies in 2017 and 2018 as first examples of S-LCA in textile manufacturing.

Chiefly among the main limiting factors to the adoption of S-LCA is the difficulty in selecting the right methodology to identify and evaluate relevant social aspects information, as well as developing specific metrics to quantitatively measure the company "social footprint" (Munõz-Torres et al., 2022). Furthermore, social impacts are calculated against identified interested stakeholders (affected stakeholders), but while the guidelines for S-LCA (UNEP, 2021) suggest the inclusion of six major stakeholders (workers, local community, consumers, other value chain actors, society, children), most S-LCA only evaluate "workers" as stakeholder group (Zimdars et al., 2018; Martin et al., 2018). Only Herrera Almanza and Corona (2020), extend the assessment to almost all stakeholders (excluding consumers and children) and also provide a linkage to the Sustainable Development Goals of the manufacturing of a cotton T-shirt.

Zimdars et al. (2018) finds that most S-LCA are limited to the activity variable of 'Working hours" and to expand the coverage to other stakeholder groups they propose to use two additional variables: 1)"Biophysical Pressure" to evaluate the impacts on the stakeholders Local community and society through an evaluation of the indirect effect of environmental impacts to the community living conditions; and 2) "Added Value" to evaluate different levels of salary and increased taxation to reflect how the specific sector investments cascade to the wider stakeholder Value chain actors.

Martin and Herlaar (2021) show that the S-LCA results are sensitive to the assumptions made for the cost of the different activities and processes in the foreground and the choice of background activities along the supply chain, since those are interconnected to processes extending beyond the supply chain of the studied system but still influencing and contributing to the final social impact assessment. The sensitivity to these data is often so high to hinder comparison between different S-LCA studies (Benoit Norris, 2014). Martin and Herlaar (2021) suggest the collection of more site-specific data along the supply chain to eliminate the noise in the final results generated by generic datasets; an approach that is followed in the study of Herrera Almanza and Corona (2020). Alternatively, Zamani et al. (2018) recommend applying a cut-off rule to reduce the number of background activities linked to the foreground system.

The limitation to translate qualitative descriptors into quantitative impact indicators capable of quantifying social impacts, hinders the S-LCA adoption. To address this issue, Neugebauer et al. (2017) propose to define a quantitative impact category based on "fair wages" as a quantitative expression of social sustainability and societal well-being, as fair wages are a prerequisite to poverty alleviation in line with the broader concept of sustainability or sustainable development. The authors consider the calculation of fair wage as a concrete midpoint impact category to link workers remuneration along the product life cycle to the social endpoint "human health" and finally to the main Area of Protection "Societal well-being" (Neugebauer at al., 2017).

Still, according to Munõz-Torres et al. (2022), the application of the current S-LCA methodology allows to obtain imperfect evidence on the textile sector social sustainability rather than no evidence at all. Finally, there is a need for a standardized, sector representative set of social indicators that are as much as possible comprehensive and objective in considering the textile supply chain social hotspots (Zamani et al., 2018;

Munõz-Torres et al., 2022).

LCC methodological gaps

In a LCC analysis, the monetary flows of the activities that contribute to the final cost of a given product are evaluated allowing to disclose the financial hotspots in the product production. The LCC mainly focuses on the product or service investment life span and excludes the contribution from upstream and downstream processes (Morone et al., 2023). As part of the production costs, the environmental and social impacts costs should also be considered in the overall product life cycle economic impact. This expanded type of LCC is specifically defined as environmental LCC (eLCC) and follows the same product system of the main LCA.

In a literature review specific to LCC conducted between 2008 and 2022, Rodrigues and da Silva (2024) retrieved only the study of Hall (2019) as an example of the application of LCC to the textile industry, although the study was meanly focused on the estimation of the additional environmental and social cost. In their case study, the authors calculated the "Sustainability Price" to produce a T-shirt in India sold in USA, by calculating the externality cost of the GHG emissions and the additional cost to meet the satisfaction of basic human needs for India (i.e., living wage gap).

Also, the study of van der Velden et al. (2017) calculates the socio-economic costs of the production of a T-shirt and a pair of jeans by evaluating the environmental externalities impacts expressed as "eco-costs" as a measure of the additional costs for a product required to prevent a specific environmental burden.

According to Amadei et al. (2021) the main limit to the use of the monetization approach for environmental impacts is the lack of harmonization and standardisation in calculating the monetary value for each environmental impact category. Rodrigues and da Silva 2024 further explain that the absence of a specific standardised nomenclature as to which type of costs (i.e., internal and external costs) should be part of the LCC, as well as which perspective (i.e., producer, consumer, communities, governments) should be applied when considering the boundary of the study, are two main limitations in applying LCC to a product life cycle.

Rodrigues and da Silva (2024) argue that the consumers' perspective will consider as internal production costs, the cost of purchase, cost of operation, cost of maintenance and repair, residual value of the product and disposal costs. Conversely, from a producer perspective they explain that the main internal costs of interest would be: raw materials acquisition, production, operation, maintenance, transport and disposal. Finally, the monetisation and internalisation of the external costs is a challenging task which requires different methodologies according to the environmental impact category selected, thus making the calculation of the eLCC quite complex (Amadei et al., 2021).

3.4.2 Discussions with industrial partner and other companies in the textile sector

Replies were obtained from a sample of ten companies involved in the textile sector, including textile manufacturing, synthetic fibres recycling and manufacturing, eco-design consultant. The majority of the respondents were from small medium companies and one company was an international textile and apparel brand. All companies reported to have used or regularly use LCA for their processes and products. Eco-design, marketing and legislation compliance (ex. France eco labelling law) were mentioned as the reasons to perform an LCA, while S-LCA and LCC were never considered.

From the answers provided, the main reasons for the little adoption of the LCA method were the lack of transparency and generic nature of the datasets, considered not representative of the corresponding materials and production process, limiting the accuracy of the results. Data on recycled content and on more innovative materials were indicated as being a limiting factor for the fibres producers. Additionally, excessive variability and lack of harmonisation between assessment methods, limitation in the interoperability between different

LCA software and little confidence in the reliability of certain impact categories assessment were indicated as reasons for the low adoption rate. The impact categories for which the least confidence was reported were biodiversity, microfibers and microplastics and social impacts evaluation. Furthermore, lack of transparency and disclosure on the modelling assumptions, background datasets chosen, and an official validation of the results stymie the credibility of the method and its extensive adoption.

Respondents indicated that data collection is a main obstacle when conducting an LCA. Lack of regional and country specific production data for input materials in databases, limited transparency due to secrecy restrictions, accessibility of LCA studies on input materials and limited availability of data on biobased raw materials were indicated as further obstacles when performing an LCA study. Upstream supply chain data were considered as being the biggest area of uncertainty by the international brand. Absence of precise information on production processes was indicated as a problem when looking at modelling the impacts from recycled secondary materials.

In addition to a general request to improve databases accuracy and coverage, extracting data on process inputs directly form the company ERP software could facilitate data collection for the life cycle inventory. A public repository of textile materials LCA studies to be used by companies at the inventory stage would also facilitate data access. In terms of methodological standardisation, the international brand supports to converge towards the use of the PEF framework across the whole sector to facilitate comparability of the results and considers investments and improvements in data acquisition as paramount to improve the efficiency of the assessment and to reduce the subjectivity of data selection and errors in data sharing.

3.4.3 Key levers to improve sustainability assessment methodologies in the textile sector

Based on the feedback received from the questionnaire, it appears that in the textile sector only the LCA is relatively common while S-LCA and LCC are not considered at all. A full sustainability assessment of textile products and textile production processes based on an objective and quantitative evaluation is therefore still uncommon in the sector.

As indicated by the respondents the following methodological improvements would favour a wider adoption of the methodology:

Databases quality

1. Improve the quality and increase the number of textile fibres production datasets. Many textile fibres are not present in current LCA databases and an increase in the number of representative datasets is necessary. Indeed, for many synthetic fibres both data availability and coverage of the production process are absent. Additionally, the datasets should better capture the different fibres raw materials production systems considering differences between areas of production importantly for natural fibres raw materials.

2. Given the need to increase the quantity of recycled fibres in fabric production, it is necessary to create datasets for recycled fibres production so to allow for a correct incorporation of recycled content in textile products.

3. Improve the modelling of natural fibres production by addressing the methodological limitations highlighted in the literature review regarding land use and water use impacts of crops cultivation methods, and evaluating besides the environmental impacts, also the social effects in terms of jobs and revenues that natural fibres cultivation/farming can offer to rural communities.

4. The inclusion of micro-fibres and micro-plastic release would allow for a fairer comparison between

natural and synthetic fibres-based textile products.

Development of consistent guidelines to harmonise modelling of textile products

5. Respondents highlighted a lack of standardisation and transparency in modelling assumptions. There is a need for a harmonised and official approach to perform LCA of textile products which requires transparency on the datasets used and for harmonisation between impact assessment methods and relevant impact assessment categories. To this end the upcoming Product Environmental Footprint Category Rules (PEFCR) for textiles and apparel products can be beneficial to create the required uniformization of assessment.

6. Additionally, an official validation of the LCA would increase the validity of the assessment.

Data access

7. Data collection was indicated as an obstacle from the companies feedbacks to perform LCAs. To this regard, in addition to quality and accuracy, data accessibility must also be increased to facilitate and simplify importing materials data when compiling the life cycle inventory. Integration of LCA software with other software (e.g ERP) would streamline inventory building, similarly to what has been proposed by Garcia-Muiña et al. (2022) and Ferrari et al. (2021). This would also allow to reduce the discretion of the analyst and increase transparency and comparability of results.

S-LCA

8. The complexity and data gaps in the textile supply chain strongly affect the ability of the S-LCA to measure the social impacts associated with a textile product. There is a need to develop more detailed databases, closing gaps at regional level and at company level.

9. Additionally, as discussed in the S-LCA methodological limitation section, it is necessary to properly quantify social indicators and link those to the functional unit of the assessed product system.

10. Finally, an international standard on how to perform a S-LCA for the textile sector would improve and generalise adoption of the methodology by indicating the main subcategories impacts linked to each stakeholder and specific for the textile industry.

11. Ultimately, besides the need for improvement of the technical aspects, there is an imperative need to link the social evaluation of textile manufacturing to legal reporting obligations and sustainability certifications. The textile sector is unfortunately dominated by powerful international buyers (i.e., retail brands) for the majority of which social sustainability is not a priority.

3.4.4 Discussions on further work needed based on results

The methodological limitations highlighted in the gap analysis and from the industrial stakeholders' feedback were also reflected in the assessment of the EREKS case study in D2.1 mostly for the LCA assessment. Considering the boundary of the studied system (i.e., limited to the washing process only), the following assessment improvement are suggested:

- Improve the identification of the transformation products from the chemical products used in the washing process and released both via the process effluents and in air during the washing process. Secondly, expand the number of CFs for ecotoxicity and human toxicity for the identified substances to more accurately evaluate their environmental impacts. New eco and human toxicity CFs are being developed as part of the WP3.

- Include the evaluation of microfiber release as part of the impact assessment method. This would require the modelling of the textile garment fibres composition, with more detailed datasets on the denim fabric composition, to better express the cause – effect chain between fabric composition and microfibers shedding during the washing process and finally their impact in the environment. Primary data on fibres shedding during the washing process should also be gathered.
- Expand the S-LCA assessment by going beyond the Job Creation Potential (JCP) impact indicator and by assessing the whole supply chain so to identify social hotspots associated with the company's activity. In fact, as per the D1.2, the number of complete S-LCA in the textile sector is very scarce and the CALIMERO project could offer an opportunity to reduce this gap. Additionally, as pointed out in the D1.2, the manufacturing process is associated with main social hotspots related to workers health and safety, labour rights and decent working conditions.
- Regarding the LCC, given the absence of LCC referring to textile products manufacturing, improvements should be directed at including the environmental cost associated with additional environmental impact categories to further contribute to the evaluation of externalities costs associated with textile products. Studies presented in the LCC literature review provide useful examples to this end.

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3.5 Biochemicals sector

3.5.1 Literature review of methodological gaps in the biochemicals sector

Bio-based chemicals include chemicals produced from materials of non-fossil, biological sources. The biochemical sector includes a wide range of industries and fields of study, including biochemistry, biotechnology, pharmaceuticals, food and beverage production, agriculture, environmental science, and more. It involves the use of enzymes, proteins, chemicals, and other biological compounds to develop new products, improve existing ones, and solve complex problems related to health, agriculture, energy, and the environment.

The main biogenic feedstocks used for producing bio-based chemicals are crops such as wheat, corn, beet, cane, palm, oilseed rape, perennial grasses, aquatic biomass, and forest residues and organic waste (De Jong et al., 2020). However, an increasing interest for forest industry by-products is apparent, such as producing valuable chemicals and engineered materials from bark, sawdust and lignin.

Several methodological gaps were identified in the literature concerning the conduct of an LCA, S-LCA and LCC for the biochemical sector. Notably, gaps related to impacts, allocations, social and economic issues were selected for emphasis. The following subsections provide a summary of each of these gaps:

LCA methodological gaps

Environmental impacts covered by LCA of biochemicals
Bishop et al. (2021) reviewed 44 LCA studies on bioplastics and alternatives. In practice, the findings and recommendations on LCA practice are applicable also for other biobased commodities (biofuels, biobased chemicals). All 44 studies included (some variation of) GWP within their impact categories. Five studies evaluated only this impact category. Beyond GWP, the most prevalent impact categories within the reviewed papers included (at least one variation of): acidification potential (29 studies); eutrophication potential (28 studies); resource depletion (26 studies); photochemical oxidant formation (23 studies); ozone depletion (20 studies); ecotoxicity (19 studies); human toxicity (17 studies); particulate matter formation (17 studies); energy (16 studies); land-use (14 studies); and water consumption (15 studies).

Based on this thorough review, the authors present an extensive list of recommendations for improved LCA practice, both for inventory practice and for impact assessment. A selection of these recommendations is reported here.

- At least should the nine aspects highlighted in the planetary boundary concept be covered in (biobased materials) LCA. Applying the PEF framework would be one way of achieving this.
- More detailed and transparent reporting of LCI data within plastic LCA studies is required (which could be said also for other LCAs), and improved effort should be made in presenting the data of the LCA studies so that the models are: 1) easily understandable; 2) transparent; 3) complete; 4) clear; 5) reproducible.
- Land use is a critical aspect of bioplastic life cycles (and other biobased products). Significant direct and indirect land use change impacts should be accounted for.
- If accounting for temporary biogenic carbon storage, studies should do so carefully with explicit EoL accounting of carbon release. Otherwise, it is better to just adopt a simplified approach in which biogenic carbon cycling is treated as GWP neutral.

Other recommendations were more specifically directed towards plastic LCAs, such as the need to capture better the aspect of plastic littering, to include additives, and be careful how to model EoL.
In another review, Weiss et al. (2012) reviewed the environmental impacts of biobased materials, with a focus on trying to find general differences in the impact when comparing biobased materials to their fossil-based counterpart. Their review analysed differences within six different impact categories:

- Non-Renewable Energy Use (NREU), quantified in gigajoules (GJ).

- Climate change, quantified in metric tons of CO_2 equivalents (t CO_2-eq) by considering the global warming potential of GHG emissions over a time horizon of 100 years.
- Eutrophication, quantified in kilograms of phosphate equivalents (kg PO_4-eq).
- Acidification, quantified in kilograms of sulphur dioxide equivalents (kg SO_2-eq).
- Stratospheric ozone depletion, quantified in kilograms of nitrous oxide equivalents (kg N_2O-eq); and
- Photochemical ozone formation, quantified in kilograms of ethene equivalents (kg ethene-eq).

Co-incidentally, also Weiss et al. (2012) reviewed 44 studies (As did Bishop et al., 2021). The relevant findings from the Weiss study are not here to discuss the general differences between biobased and fossil-based products, but rather the key methodological issues that were discussed in the study. These were:

- The need to include indirect land use and its further implications (e.g., biodiversity) in assessment of biobased materials, essentially because more land will be needed to produce more biobased raw material.
- Treatment of agricultural residues. The impact of biobased product systems can be largely reduced if such residues can be valorised, without damaging the soil re-fertilization. The same would apply to forestry residues.
- Farming practices play an important role in the impact of biobased systems, and there are big differences in the environmental impacts stemming from different agricultural practices.

Allocation method

Allocation involves distributing environmental burdens among co-products in the LCA of multifunctional systems. This allocation can be based on physical properties such as mass or energy content, or on the economic value of the process streams. ISO 14040 advises avoiding allocation, when possible, either by subdividing the process into subprocesses related to co-products or by expanding the system boundaries to include additional functions, known as system expansion. In biochemical production systems, the choice of allocation method significantly impacts results (Börjesson, and Tufvesson, 2011). Many reviewed LCAs opted for physical allocation, while some presented results for both physical and economic allocation (Tufvesson and Börjesson, 2008). System expansion likely provides the most reliable results but requires more inventory data and time. The choice of which system is being replaced and the extent of product replacement also influence results, increasing uncertainty with more data.

Physical allocation is time-independent but does not account for product quality differences. For example, in chemical processes, low-value by-products may share the environmental burden equally with the main product, which can be misleading, especially for fine chemicals and pharmaceuticals where waste streams are substantial and added value per process step is significant. Economic allocation faces the challenge of fluctuating prices, but prices of raw materials are often interconnected (Börjesson and Tufvesson, 2011). It is advisable to present results using different allocation methods or discuss the potential impact of alternative methods. For bulk chemicals, system expansion is recommended to include benefits from by-products. For fine chemicals, economic allocation is suggested since by-products generally have lower value compared to the main product (Tufvesson et al., 2013).

Carbon footprint

Conducting a LCA for the biochemical sector reveals several methodological gaps, particularly in accounting for the carbon footprint. One significant issue is the inconsistent methods used for calculating and reporting GHG emissions. Different studies may use varying boundaries for system processes, include different stages of production, or apply diverse emissions factors, leading to incomparable results. This lack of standardization makes it difficult to accurately assess the environmental impact of biochemical processes and products, hindering efforts to develop industry-wide benchmarks and regulations.

Another critical gap in this issue is the treatment of biogenic carbon, which is carbon that is sequestered in biological materials such as plants and algae. Current LCA methodologies often fail to adequately address the complexities of biogenic carbon accounting. For instance, there is debate over whether to consider the carbon absorbed during the growth of biomass as a credit or to account for it differently when the biomass is converted into bio-based products. This can lead to significant discrepancies in the reported carbon footprints of biochemical products, complicating the evaluation of their true environmental benefits or drawbacks (Moro and Helmers, 2017).

S-LCA methodological gaps

Based on a systematic literature review, Rebolledo-Leiva et al. (2023) summarized the methodological gaps of S-LCA application on bioeconomy as follows; “boundaries definition, cut-off criteria, multifunctionality, data availability, impact assessment methods, uncertainty, and results interpretation”. Some more specific methodological gaps are defined in the following paragraphs.

Social impacts of a product are very much dependent on the location of production and the regulations and overall situation of the country of production. Therefore, each actor in the value chain and its location is important. In the biochemicals industry, as well as any other industry, the location of production of end-product can be far from the raw material production and this situation has an important impact on the social issues to be addressed.

One of the pilot projects on guidelines for S-LCA is “Social Impact Assessment of Fuji Oil’s Shea Value Chain”. In this example, shea fruit kernels are collected, roasted, and fermented in villages in Ghana, the kernels are processed into shea butter in a crushing facility, stearin is separated from shea butter in another facility in Ghana, but the stearin is used to make beauty products in Belgium and Singapore (Davis and Ascencio, 2022). While carrying out S-LCA, first the subcategories to be assessed are chosen based on the important social issues. If there is a residence area where indigenous people are living around the production facility the subcategory “Respect of indigenous rights” is an important topic for the assessment. Or the reference scale prepared for “Health and safety” in a factory might be useless for assessing the health and safety of fruit collectors in a village. Therefore, ideally each link in the value chain needs to be assessed in its own means. In the above example the value chain is not extremely complicated since there are two countries where the production takes place but for some other cases, with more countries in the value chain, it can be overly complicated. How to approach a net of value chain activities in different countries and in different situations (facility vs individual workers) in an S-LCA study is a gap in the methodology.

Davis and Ascencio (2022) points out another topic related to the development of reference scales specific to each study. They discuss that although developing reference scales for each study can be useful for the case owner, availability of baseline reference scales could ease the development of reference scales specific to each study. Developing reference scales generic for biochemical sectors which can be modified to fit in different cases can be a solution for this problem.

LCC methodological gaps

Identifying methodological gaps in LCC for the biochemical sector is crucial for enhancing the accuracy and reliability of economic assessments in this industry. The biochemical sector, which deals with the production of bio-based chemicals from renewable resources, faces unique challenges due to its emerging technologies, diverse supply chains, and sustainability concerns. Here are some common methodological gaps:

Lack of standardized LCC framework and data limitation

Unlike more established industries, the biochemical sector lacks a universally accepted LCC methodology or standards that are widely recognized. This inconsistency in the application of LCC methods can lead to variations in results, making it difficult to compare findings across different studies. Diverse approaches in cost allocation for by-products, capital investments, operational costs as well as various prices for products create variability in cost estimates (Swarr et al., 2011; Zeug et al., 2021). Moreover, the biochemical sector often involves emerging technologies, resulting in limited operational data, uncertain future costs, and high sensitivity to market fluctuations (e.g., raw material costs, policy changes, etc.). High levels of uncertainty regarding input costs, technological performance, and market demand limit the accuracy of LCC predictions. The cost of feedstock or production processes may vary significantly depending on the region or technological maturity, making predictions highly uncertain (Ramasamy et al., 2015).

Scale of operation

Many LCC assessments in the biochemical sector are conducted for small-scale or pilot operations, but they may not accurately reflect costs at commercial-scale production. Extrapolating costs from small-scale to large-scale operations without accounting for scaling effects can lead to misleading economic estimates. Pilot-scale costs for bio-based chemical production may be higher than commercial-scale costs due to lack of economies of scale. In the biochemical sector, pilot-scale production of bio-based chemicals, such as succinic acid, often incurs higher costs per unit due to limited economies of scale, inefficient process optimization, and higher capital and operational costs. These pilot-scale operations typically use custom equipment and smaller batch sizes, which increase per-unit costs compared to larger commercial-scale facilities that benefit from optimized processes, bulk purchasing, and economies of scale. Extrapolating these higher pilot-scale costs directly to commercial-scale production can result in misleading economic estimates, as it fails to account for cost reductions achieved through scaling up and improved efficiency in larger operations (Erakca et al., 2024).

EoL costs

In many LCC studies for biochemical processes, EoL costs, such as disposal, recycling, or waste management, are either underestimated or ignored. The exclusion of EoL costs can distort the true long-term costs of biochemical products, especially those related to environmental impact or regulatory compliance. A biochemical product that generates non-degradable waste may have significant disposal costs that are not reflected in its life cycle cost analysis.

Shen et al. (2009) provide insight into the challenges associated with EoL costs for bio-based plastics, a crucial aspect of LCC. In LCC assessments, EoL costs encompass disposal, recycling, or composting processes. For bio-based plastics, these costs can be particularly complex due to variations in how these materials are treated at their end of life compared to conventional plastics. The problem lies in the fact that bio-based plastics often have different degradation pathways and recycling requirements. Many bio-based plastics are designed to be biodegradable or compostable, but the infrastructure for such waste management is often insufficient or not widely implemented. This can lead to higher costs for proper disposal and potentially result in bio-based plastics being mismanaged or sent to landfills, which undermines their environmental benefits and affects overall cost estimates. Additionally, the market for bio-based plastics is still developing, and EoL processing methods are not uniformly established. This uncertainty can lead to inaccuracies in LCC assessments, as the costs associated with EoL management may be underestimated or not fully accounted for. The lack of standardized EoL treatment options and the variability in local waste management practices contribute to these challenges, making it difficult to accurately predict the total lifecycle costs of bio-based plastics.

Inclusion of externalities

LCC traditionally focuses on direct economic costs (capital, operational, and maintenance costs), but in the biochemical sector, externalities such as environmental and social costs (e.g., carbon emissions, biodiversity loss, job creation) are often overlooked. Ignoring externalities can result in an incomplete picture of the true costs associated with bio-based products, leading to suboptimal decisions from a sustainability perspective. The environmental impact costs include the costs associated with emissions, waste, and resource depletion that are not directly accounted for in LCC but affect overall sustainability. For example, the production of bio-based succinic acid involves lower GHG emissions compared to petrochemical alternatives, but if the cost of these environmental benefits is not included, the bio-based option might appear less economically favorable.
Bassi et al. (2021) highlights key issues regarding the inclusion of externalities in LCC for polyhydroxyalkanoates (PHA) production from urban biowaste. Specifically, the study examines how the failure to incorporate externalities—such as environmental and social impacts—can significantly skew the economic evaluation of PHA production. While traditional LCC focuses on direct costs, such as raw materials, energy, and labor, it often neglects the broader externalities like reduced GHG emissions, improved waste management, and health benefits associated with bio-based PHAs. The main problem is that without integrating these externalities, the LCC might underestimate the true value of bio-based PHAs. For example, the environmental benefits of PHAs, which are biodegradable and reduce landfill waste compared to conventional plastics, are not reflected in the direct cost analysis. This omission can make bio-based PHAs appear less cost-effective compared to conventional alternatives, which overlook their long-term sustainability advantages. By including these externalities, the LCC could better capture the overall economic and environmental benefits, providing a more accurate assessment of the true value and impact of PHA production.

3.5.2 Discussions with industrial partner and other companies in the biochemicals sector

A total of four organizations were interviewed. One focusing on developing and producing specialty chemical solutions for the pulp and paper industry. The second one, specializes in biofuel production from renewable sources. The third one as a green chemical company dedicated to producing bio-based chemicals. The last one produces a wide range of chemicals used across various industries, including agriculture (e.g., crop protection), the automotive sector (e.g., fuel additives), and construction (e.g., foams and engineering plastics).

When asked about gaps in the LCA/LCC/S-LCA methodology that they have faced during assessments, all representatives highlighted key challenges with the LCA and related methodologies, specifically regarding data consistency, transparency, and access to accurate information from suppliers. Their responses reveal both common and unique issues, which can be summarized as follows:

Data consistency and transparency

The representatives observed inconsistencies in data handling within LCA methodologies, particularly concerning raw material origin and treatment across regions. These inconsistencies can lead to variations in CO_2 assessments, which ultimately impact the overall transparency and accuracy of assessments. For example, CO_2 load assessments for raw materials differ based on regional values, causing discrepancies in carbon footprints for the same material sourced from different locations. There are also challenges with suppliers who lack the expertise or routine to consistently provide accurate data. This gap complicates the collection of inventory data and results in unreliable information for raw material assessments.

Inconsistent treatment of waste vs. virgin materials

The representative highlighted that waste streams and virgin materials are often assessed inconsistently. Waste streams are often assumed to start at the point of waste creation, while virgin materials require full tracing to their original source, leading to discrepancies. Moreover, due to favorable legislation, waste streams are sometimes perceived as more sustainable even if they share the same origin as virgin materials. This inconsistency does not necessarily reflect real-world conditions and can skew assessment results.

Supplier limitations in data provision

A significant gap in LCA data quality arises from suppliers' limited ability to provide accurate and complete inventory data. This is partly because many suppliers lack the knowledge or routine experience with climate assessments, making it challenging for them to perform detailed, one-off calculations for individual chemicals. Furthermore, suppliers often act as intermediaries, buying and selling products without direct involvement in production. As a result, they cannot provide critical information about production site distances or the specific electricity mix, both of which are essential for accurate climate assessments. Moreover, based on the responses there are still challenges in calculating emissions related to transportation and procurement of components for buildings, suggesting reliance on certification schemes when possible.

Application-based variability in fossil fuel assessments

They expressed concerns about the different climate performance ratings assigned to fossil fuels depending on their application. This variability complicates the interpretation of LCA results, as the same fuel can have different environmental impacts based on its intended use. This gap suggests a need for more standardized criteria that apply uniformly across applications.

Limitations in handling biogenic carbon

The companies mentioned the need for better accounting of biogenic carbon in LCA methodologies since highlighted that biogenic carbon should be considered differently than fossil carbon, especially in cradle-to-gate assessments, as it offers temporary storage that fossil fuels do not. They also expressed a similar sentiment regarding the inclusion of biogenic carbon in their assessments. The limited treatment of biogenic carbon in standard LCA methodologies creates a gap in reflecting the environmental value of renewable resources. Addressing this would involve revising methodologies to provide accurate carbon credits and recognize biogenic carbon's temporary sequestration effects.

When asked about the quality of existing impact categories and potential areas for improvement, they provided insights into potential improvements for assessing impact categories within LCA methodologies. Their responses emphasize the need for standardized practices, better data management, and more precise measurement techniques. Here's a summary of their suggestions:

Development of new standards and fair assessments

They acknowledged that improved standards could significantly enhance the assessment of bio-based chemicals and other impact categories. They advocated for the creation of new standards for bio-based chemicals and plastics, learning from existing frameworks used for biofuels. This approach would allow each substance to be assessed fairly and individually, rather than being grouped into broad categories that may not capture the unique environmental impact of each material.

Leveraging databases for improved data accuracy

The representatives highlighted the use of established databases to address gaps in inventory data. It was suggested using the Ecoinvent database as a primary source for inventory data. If exact data is unavailable, an average of all input chemicals could be used to fill in gaps. This approach can offer more consistency and reliability in assessments where supplier data might be incomplete or unavailable.

Anticipated improvements in transportation data standards

They expressed optimism that transportation companies will soon adopt standardized practices for tracking and reporting their organizational carbon footprints. As this becomes common practice, it will likely become easier to access accurate and consistent data on transportation-related impacts in the coming years, enhancing overall LCA accuracy.

Enhanced measurement techniques for specific electricity consumption

They pointed out the challenge of accurately measuring electricity consumption at the machine level, noting that one way to achieve this could be to install counters on individual machines. However, this would require collaboration with electricians to implement on a larger scale. Such precise measurements could help refine LCA results by allowing more detailed insights into energy use for specific processes.

3.5.3 Key levers to improve sustainability assessment methodologies in the biochemicals sector

Here are key levers to improve sustainability assessment methodologies for the biochemical sector based on the identified gaps:

- **Standardize data handling across regions**: Implement consistent methodologies for CO_2 load assessments and raw material evaluations across regions to reduce discrepancies in carbon footprint calculations.
- **Develop new standards for bio-based chemicals**: Create assessment standards specific to bio-based chemicals and plastics, like those used for biofuels, ensuring fair and precise evaluations for these materials.
- **Enhance supplier education and engagement**: Train suppliers on the importance and methods of climate assessments to improve the consistency and reliability of the data they provide, especially for those who only act as intermediaries.
- **Leverage comprehensive databases**: Use established databases, such as Ecoinvent, as primary sources for inventory data, and consider averages for chemicals when exact data is missing to improve data consistency and fill data gaps.
- **Improve biogenic carbon accounting**: Modify LCA methodologies to differentiate biogenic carbon from fossil carbon, accounting for its temporary sequestration and other unique environmental benefits.
- **Increase transparency in waste vs. virgin material assessment**: Standardize the treatment of waste and virgin materials in LCA to reflect their real-world environmental impact more accurately, mitigating legislative biases.
- **Anticipate improved transportation data standards**: Prepare for upcoming standardized practices in transportation carbon footprint reporting, as these will likely enhance data accuracy in transportation assessments over time.
- **Install precise measurement systems for electricity use**: Encourage the use of individual machine-level electricity counters, which could enable more accurate assessments of energy consumption for specific processes.

3.5.4 Discussions on further work needed based on results

To improve sustainability assessment methodologies in the biochemical sector, significant work is required to develop consistent standards for CO_2 load assessments and raw material evaluations across regions. By engaging industry stakeholders and regulatory bodies, companies can establish protocols that mitigate regional discrepancies, ensuring more accurate carbon footprint calculations. Creating specific standards for bio-based materials, like those used for biofuels, would allow fair and precise evaluations of these resources and highlight their environmental benefits. To support data consistency, suppliers should be trained in standardized reporting tools and sustainability metrics, allowing them to better capture and communicate data critical to LCA processes.

Additionally, leveraging comprehensive databases, such as Ecoinvent, could address gaps in supplier-provided data, ensuring reliable assessments even when specific data is unavailable. Improved handling of biogenic carbon is also essential, as existing methodologies often overlook its temporary sequestration benefits. By refining these methodologies and incorporating findings from case studies on biogenic carbon storage, assessments will better reflect the true environmental impact of renewable resources, promoting balanced assessments of fossil and bio-based materials. Consistency in treating waste and virgin materials within LCAs will further harmonize outcomes, as current methodologies sometimes favor waste streams due to legislation, leading to inconsistencies in sustainability evaluations.

Finally, as transportation companies standardize their carbon footprint reporting, these advances can be integrated into LCA processes to improve the accuracy of transportation-related emissions data. Enhanced measurement of machine-level energy consumption would also allow for a more granular view of energy use in specific processes, ultimately refining LCA outcomes. Together, these steps can build a more reliable, actionable framework for sustainability assessments in the biochemical sector, empowering companies to make informed decisions that support sustainable goals.

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4 CONCLUSIONS

This report was written within T2.4 in the CALIMERO project. The report presents methodological gaps in sustainability assessment within the five bio-based sectors included in the project (i.e., construction, woodworking, pulp and paper, textile and biochemicals). The aim of the document was to identify key levers for improvement of assessment methodology for the five sectors to be used in methodological development further on in the project. The focus of the assessment methodology was on all three dimensions of sustainability, i.e., environmental, social and economic domains.

4.1 Methodological gaps within sustainability assessment methodology

A variety of methodological gaps were identified across the sectors, including environmental, social and economic perspectives of assessment methodology.

4.1.1 Methodological gaps for LCA

Within methodological gaps for LCA, gaps identified across several sectors included those for biogenic carbon, indicators for land use and biodiversity, eco- and human toxicity impacts, air quality and health impact, how to handle multifunctionality as well as gaps in inventory data. The findings in the literature review were found to resemble in the gaps identified from the contacts with stakeholders.

Using the PEF method to account for biogenic carbon was highlighted as an issue both in the literature reviews and the contacts with stakeholders across the sectors. It was pointed out that the PEF methodology does not consider the carbon removal as a credit for plants during the photosynthesis process, as well as the effect of climate change mitigation when the carbon is stored for extended periods for long-lasting applications (e.g., construction), producing a no-differentiation effect when it is compared to their fossil-based counterparts.

With regards to biodiversity, both in the literature as well as within contacts with stakeholders, it was lifted that the impact category is not well reflected within current PEF methodology. Instead, land use is seen as a proxy indicator in current methodology. However, it focuses primarily on the number of species in an ecosystem, which is not the only determinant for measuring changes in biodiversity. Hence, applying the PEF methodology does not allow for a comprehensive assessment of the differences between agricultural and forest activities, which is of importance across all sectors studied.

With regards to gaps in inventory data, stakeholders lifted several aspects such as outdated models, large need for inventory data for assessing certain impact categories, as well as lack of data within professional LCA databases. In particular, many actors lifted that high-quality and transparent datasets for bio-based materials are not easy to find, such as regional or country-specific data, and that they instead rely on proxies or outdated data or see the need of collecting data through time consuming literature searches. There are also challenges with suppliers who lack the expertise or routine to consistently provide accurate data. This gap complicates the collection of inventory data and results in unreliable information for raw material assessments.

Handling multifunctionality is of special importance within bio-based sectors as agriculture and forestry and the subsequent processing of the materials often generate several outputs. Additionally, the waste handling at the EoL may also generate recyclable or reusable materials as well as heat and/or electricity. Key challenges include determining how to allocate the environmental impacts of these materials across multiple cascading cycles and incorporating quality parameters, as the future reusability and recyclability of materials depend on their condition at the EoL stage.

Impact assessment methodology in eco- and human toxicity was highlighted as a gap in several sectors. For example, assessing the impacts from the use of chemical products was seen as complex due to the lack of transparency on the composition of the chemical product and the resulting degradation products.

4.1.2 Methodological gaps for S-LCA and LCC

With regards to social and economic assessment methodology, findings of gaps in the literature included lack of inventory data and databases, handling multifunctionality and gaps in the impact assessment methodology.

Concerning lack of inventory data and databases, this was highlighted for economic assessment with e.g., incomplete data regarding the environmental externalities with various production stages, as well as lack of detailed data on indirect costs, making it difficult to integrate these costs into LCC assessments. Moreover, data collection across different lifecycle stages, from raw material extraction to disposal, is often incomplete or inconsistent, leading to gaps in economic assessments. This incomplete data limits the accuracy of evaluating long-term economic impacts, particularly for costs that span beyond direct operations, such as EoL waste management or emissions abatement.

With regards to handling multifunctionality for economic assessments, a gap was found related to no clear consensus in LCC methodologies on how to allocate costs and revenues related to by-products in some of the bio-based sectors studied. For example, within the pulp and paper sector, the lack of a standardized approach for allocating costs in biorefineries presents a challenge for comparisons between different processes or companies. This leads to inconsistencies in LCA and cost assessments, complicating efforts to improve sustainability. Different allocation methods can also lead to significantly different outcomes, affecting the perceived profitability and environmental sustainability of the biorefinery processes. The selection of an appropriate allocation method often involves subjective judgement, and there is no universally accepted standard. The preferences of decision-makers and stakeholders play a critical role, making it difficult to achieve consensus across industries and regions.

Similarly, a current issue in assessment methodology is how to account for EoL costs. For example, within the biochemicals industry, many LCC studies for biochemical processes either underestimate or ignore EoL costs, such as disposal, recycling, or waste management. The exclusion of EoL costs can distort the true long-term costs of biochemical products, especially those related to environmental impact or regulatory compliance. A biochemical product that generates non-degradable waste may have significant disposal costs that are not reflected in its life cycle cost analysis.

In contact with stakeholders within the industries in CALIMERO, assessment methods for social and economic perspectives were found to be rarely used. One reason for not using these were that stakeholders had access to other tools and systems to detect these kinds of problems and to work with improvements. Moreover, the stakeholders generally mentioned the lack of available high-quality data for assessing these perspectives and that the quality of the results in social and economic assessment were believed to be lower than those resulting from an environmental LCA.

4.2 Key levers for improvement of sustainability assessment methodology in the bio-based sectors studied

4.2.1 Levers related to input data

- Enhancing the availability of high-quality data for bio-based materials in LCA databases. With enhanced data quality and availability, decision-makers can ensure that comparisons between bio-based and fossil-based materials are grounded in reliable information, leading to more informed and sustainable choices.
- Leverage comprehensive databases: Use established databases, such as Ecoinvent, as primary sources for inventory data, and consider averages for chemicals when exact data is missing to improve data consistency and fill data gaps.

- Enhance supplier education and engagement. Train suppliers on the importance and assessment methods to improve the consistency and reliability of the data they provide, especially for those who only act as intermediaries.

4.2.2 Levers related to circularity indicators in assessment methodology

- Integration of circularity indicators into the LCSA framework: Many bio-based materials reaching the EoL stage retain the potential for reuse or recycling in other life cycles. Establishing standardized circularity indicators will provide clearer guidelines for assessing and promoting material recovery and reuse in line with LCSA methodologies.
- Develop guidelines for handling multi-output processes: Production systems within the studied bio-based sectors may have multiple outputs. How these are handled and how the impacts of the system are allocated influences the outcome significantly.

4.2.3 Levers related to accounting for sequestration and emissions of carbon and its dynamics

- Implementation of dynamic LCA models for holistic calculations of sequestration and emissions of carbon over time.
- Establish a reliable and clear methodology for estimating the biogenic carbon contained in products, especially for bio-based products.
- Implement a comprehensive cradle-to-grave approach for ensuring that credits of biogenic carbon sequestration are considered throughout the product’s life cycle. This would imply modifying LCA methodologies to differentiate biogenic carbon from fossil carbon, accounting for the carbon uptake during the growth phase and the emissions at the EoL.
- Encouraging the use of bio-based materials in long-lasting applications. This would help sequester carbon for extended periods and promote a circular economy.

4.2.4 Levers related to assessment methodologies for land use, ecosystem services and biodiversity

- Improvement of the LULUC indicator and development of a standardized methodology to incorporate indirect Land Use Change (iLUC).
- Development of comprehensive and dynamic indicators to capture ecosystem services and biodiversity: to account for differences between monoculture and permaculture, spatial and temporal variability and include indirect and long-term impacts such as habitat fragmentation leading to biodiversity loss or soil degradation affecting agricultural productivity.

4.2.5 Levers related to assessment methodology for eco- and human toxicity

- Develop dynamic characterization models to enhance understanding of how the environmental and health impacts of certain exposure to chemicals change over time.
- Improve stakeholder engagement including researchers, industry professionals, and policymakers for creating toxicity models that accurately reflect real-world scenarios and address community concerns.

4.2.6 Levers related to socioeconomic impact assessment methodology

- Develop consistent and comprehensive internationally recognized methodological procedures and guidelines for S-LCA and LCC across sectors, enabling fair comparability between products/companies. This should include perspectives of temporal variability in material lifecycles as well as inclusion of circularity and EoL scenarios.

- Develop impact assessment methods within S-LCA to account for positive impacts as well as impact categories related to specific stakeholders.
- Develop more detailed databases for socioeconomic assessments.

4.3 Further work within CALIMERO

- Development of robust and scientifically sound methodologies for assessing impacts on biodiversity, ecosystem services, new characterization factors for eco- and human toxicity of chemicals frequently used in bio-based industries.
- Improve handling of biogenic carbon accounting, including taking into consideration the uptake of biogenic carbon by plants and implementing a cradle-to-grave approach
- Development of the dynamics of carbon to take into account timing of carbon storage and release for the carbon footprint of the case studies.
- Incorporation of advancements of impact assessment methodologies, in future work, with improvement of case studies (WP5) within the project, to enable a more comprehensive and holistic environmental analysis.
- Improve handling of multifunctionality from recycling e.g., for the pulp and paper sector, through extending the scope of case studies from cradle-to-gate to cradle-to-grave to include EoL.
- Include the evaluation of microfiber release as part of the impact assessment method for the textile sector. This would require the modelling of the textile garment fibres composition, with more detailed datasets on the denim fabric composition, to better express the cause – effect chain between fabric composition and microfibers shedding during the washing process and finally their impact in the environment. Primary data on fibres shedding during the washing process should also be gathered.
- Develop circularity indicators and criticality aspects with the objective to integrate circular economy and criticality aspects into the LCSA framework. In this sense, the way in which the cascading of bio-based products use can be taken into account for reuse or recycling will be evaluated, as well as the level of criticality of the type of bio-based products used in the case studies according to the socio-economic context of the area.
- Contribute to developing socioeconomic impact assessment methodology for the bio-based sectors. For example, to consider the potential jobs created in the value chain of the production processes in the bio-based sectors, divided depending on if the job created is related to the bio-economy or not, apart from other key aspects such as the skill level (i.e., low, medium or high) or gender.
- Expand the S-LCA assessment by going beyond the job creation potential impact indicator and by assessing the whole supply chain, in order to identify social hotspots associated with the company activity.

5 Appendix

5.1 Template for interviews and contact with industrial partners and companies

QUESTIONS ON GENERAL INFORMATION

Question number	Question	Answer
#1	Company name	
#2	Company sector	
#3	Main focus of company	
#4	Size of company (number of employees)	
#5	Description of your role in the company	
Observations		

QUESTIONS ON LIFE CYCLE METHODOLOGIES

Question number	Question	Answer
#6	Are you using Life Cycle Assessment (LCA), Life Cycle Costing (LCC) or Social Life Cycle Assessment (S-LCA) in your current role? *- If yes, go to question #10* *- If no, go to question #7*	
#7	Have you ever used LCA/LCC/S-LCA in another context? (e.g., during another position/in studies/other context?) *- If yes, go to question #8* *- If no, go to question #9*	
#8	What was the industry that you have used the life cycle methodologies for?	
#9	Describe if and how LCA/LCC/S-LCA might be useful for the company you are working for	
#10	What is your main purpose in using LCA/LCC/S-LCA? (e.g., reporting, product development, product declaration/labelling, etc.)	
Observations		

QUESTIONS RELATED TO GAPS IN LCSA METHODOLOGY AND LEVERS TO ADDRESS THESE IN THE SPECIFIC SECTOR

Question number	Question	Answer
#11	In your opinion, what are the gaps in the LCA/LCC/S-LCA methodology that you have faced during assessments?	
#12	Which impact categories are not well developed?	
#13	How could the assessment of those impact categories be improved?	
#14	Have you faced data (foreground or background) collection problems during the assessment? What was the problem? Please, suggest any method you follow to overcome those problems	
#15	Describe other kinds of problems you have faced during the assessments. How would it be possible to overcome those problems?	
#16	Are there any other methods that you use for sustainability assessment? (e.g., carbon footprint, GHG protocol etc.). What gaps do you see related to these methods?	
Observations		

QUESTIONS RELATED TO GAPS IN LCSA METHODOLOGY AND LEVERS TO ADDRESS THESE WITHIN THE CALIMERO CONTEXT

POTENTIAL ADDITIONAL PART TO QUESTIONS 11-16, IN CASE THESE PERSPECTIVES HAVEN'T BEEN MENTIONED ALREADY. ACADEMIC PARTNER DESCRIBE/SHOW THE MAIN RESULTS FROM THE LITERATURE REVIEW AND CASE STUDIES.

Question number	Question	Answer
#17	Based on the results from the literature review and the case studies within the specific sector, which of these gaps have you discovered in your work?	
#18	How could the assessment of those impact categories be improved?	
#19	Have you faced data (foreground or background) collection problems during the assessment? What was the problem? Please, suggest any method you follow to overcome those problems	
#20	Describe other kinds of problems you have faced during the assessments. How would it be possible to overcome those problems?	

FINALIZATION AND FURTHER WORK

Question number	Question	Answer
#21	Do you suggest any other person we can do a similar interview with?	
Observations		