CALiMERO

IMPROVING BIO-BASED INDUSTRIES LIFE CYCLE SUSTAINABILITY

D5.5

Guidelines and recommendations for sustainability performance

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Abstract:	This report presents a comprehensive review of sustainability performance barriers and opportunities across five bio-based sectors —construction, woodworking, textiles, pulp and paper, and biochemicals— identified during the CALIMERO project. Environmental hotspots are primarily driven by material inputs and energy use, with sector-specific pressures such as forest resource demand in construction, woodworking and pulp & paper, and energy- and chemical-intensive processes in textiles and biochemicals. Other challenges include product durability, circularity, and labour conditions. Across sectors, key barriers include limited and non-representative data, fragmented life cycle impact assessment methodologies, and financial or technological constraints, particularly for SMEs. The study identifies opportunities to improve sustainability, including enhancing circularity and industrial symbiosis, adopting traceable and safer inputs, and optimizing production processes. Implementing these measures can support a more sustainable, bio-based industry while avoiding the creation of new environmental hotspots and fostering economic and social value.

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1 INTRODUCTION

1.1 Engagement of stakeholders for achieving a sustainable development

Sustainability is an inherently interdisciplinary concept that integrates knowledge from a wide range of fields. It is closely linked to traditional scientific disciplines such as physics, chemistry, and economics, particularly in areas like climate change modelling, pollution analysis, and the valuation of environmental assets. In addition, emerging areas such as environmental engineering and sociology also contribute valuable perspectives and approaches to sustainability (Fernandes & Rauen, 2016).

On the one hand, environmental engineers can serve as key facilitators in the decision-making process by applying evaluation methods that help identify and propose sustainability improvement strategies. In this context, the Life Cycle Sustainability Assessment (LCSA) methodology stands out as one of the most widely applied and internationally recognized approaches for assessing the sustainability impacts of products or services across their entire life cycle, including stages such as research and development, design, raw material acquisition, manufacturing, distribution, use, maintenance and end-of-life (Costa et al., 2019).

On the other hand, sociologists have become increasingly involved in sustainability-related research over the past few decades, particularly with the emergence of novel concepts addressing the multiple dimensions of human behaviour. These behaviours can either support sustainability (e.g., environmental awareness) or hinder it, such as through greenwashing or climate change inaction. In this context, the work of the environmental psychologist Robert Gifford is particularly noteworthy. He identified over 30 psychological barriers to climate action (referred to as "dragons of inaction") which are categorized into thematic groups or "dragon families," including limited cognition and behaviour, ideologies, social comparison, among others (Gifford, 2011).

As a consequence of the above, it is deducted that sustainability is a concept that (due to its multi-dimensional configuration) must be approached by taking into consideration three key pillars: environmental, economic and social, as this should not be considered exclusively about minimizing or reducing environmental burdens, but also ensuring both social well-being and long-term economic viability. In addition, apart from being addressed in a holistic way, sustainability evaluation should involve as many stakeholders as possible, building bridges between science, technology and society (Martiny et al., 2024).

By "stakeholders" we refer to any individual or group —such as customers, employees, suppliers, shareholders, and communities— whose cooperation and engagement is necessary to establish a path for ensuring the pursuit of sustainable development (Braun et al., 2019). Stakeholder involvement in the sustainability domain depends on a complex web of relationships between internal actors in the organization (e.g., owner, managers or employees), external actors in the operating environment (such as suppliers, customers, competitors, activist groups or media), and broader natural and institutional systems by means of four main forces: (i) sociocultural, (ii) technological, (iii) economic and (iv) political/legal (Sady, 2023).

All these stakeholders interact and influence each other to a greater or lesser extent, in both positive and negative ways. It is therefore of paramount interest in the pursuit of sustainable development to promote not only the positive, but also the greater interactions over the negative ones. Additionally, to get the most out of it, this should be reciprocal, in such a way that the academic stakeholders provide the technical knowledge (in terms of the analysis methodology following a life cycle and sustainability perspective), while the industrial stakeholders show more practical content (of the case study to be analysed). Then, this knowledge serves as a basis to lay the foundations of a proper life cycle management system in which technical sustainability results are considered in the practical decision-making process (Nilsson-Lindén et al., 2021).

In this respect, the CALIMERO project is a good example of how industrial and academic partners are working together to improve the sustainable performance of five targeted bio-based sectors (i.e., construction, woodworking, textiles, pulp and paper, and biochemicals). Within the framework of this project, a series of guidelines have been developed to address key sustainability needs identified across these five industries in the bioeconomy. These guidelines highlight sector-specific challenges that must be overcome to achieve meaningful progress and provide tailored recommendations for industry stakeholders, who play an essential role in shaping a more sustainable future.

1.2 Main aim and objectives

The primary objective of this document is to provide a series of guidelines and recommendations for the industry stakeholders in five target sectors of the bioeconomy. To that end, a series of secondary objectives have been established, including:

- Compile all the learnings in terms of sustainability performance barriers to be improved from previous documents of the CALIMERO project. Particularly, the following ones will be reviewed and adapted to the requirements of the current report:
    - D1.1 Data collection from industry current practices: state-of-the-art and identification of gaps.
    - D1.2 Hotspot analysis of most impactful industrial processes.
    - D1.4 Theory of change and system incentives & penalties analysis.
    - D2.2 Identification and implementation of appropriate modelling strategy.
    - D2.5 Key levers for improvement of sustainability assessment methodology (public version).
    - D5.1 Potential solutions to improve the performance.
    - D5.2 Potential cross-sectorial solutions.
- Transform sustainability performance needs into a series of guidelines and recommendations in a particularized way for each of the five-target bio-based sectors of the CALIMERO project.
- Obtain conclusions from the insights obtained, identifying further sector-specific work to be conducted in the future to align bioeconomy with a sustainable future.

1.3 Report structure

Section 2 identifies the most impactful processes in each bio-based sector. Section 3 addresses the sustainable performance barriers detected in the CALIMERO project for the construction (Section 3.1), woodworking (Section 3.2), textiles (Section 3.3), pulp and paper (Section 3.4) and biochemicals (Section 3.5), as well as other limitations common to all bio-based sectors (Section 3.6). Sector 4 then focuses on translating this information into a set of opportunities for improvement to each of the aforementioned sectors. Finally, the main conclusions derived from the analysis are presented in Section 5.

2 MOST IMPACTFUL BIO-BASED PROCESSES

The environmental hotspots across the five bio-based sectors of the CALIMERO project were identified in **D1.2**, based on existing methodologies and tools. The main findings are summarized below, highlighting both the most relevant environmental impact categories and the key activities that contribute most significantly to the overall single-score results.

In the **construction sector**, a significant portion of the bio-based products used are derived from wood, meaning that many of the processes and materials relevant to this sector are already included in the woodworking analysis. Therefore, the findings discussed in the woodworking part can be considered representative of the production and transformation of wood into semi-finished products commonly used in construction. Focusing specifically on the 18 construction processes that do not fall under the woodworking category, most present hotspots in the impact categories of climate change and fossil resource use (17 processes each), followed by mineral and metal resource use (16 processes), particulate matter (15), and acidification (13). Conversely, categories such as ozone depletion, ionizing radiation, human toxicity (non-cancer), and marine and freshwater eutrophication do not appear as hotspots in any of these processes.

In terms of contributing activities, material provisioning is responsible for 80% of the identified hotspots. This includes both non-bio-based materials —such as low-alloyed steel, nickel (used in coatings), and glass— which alone account for 48% of the hotspot processes, and wood-based materials, both raw and processed, which contribute 18%. Additional contributors include alkyd paints and chemicals such as boric acid (10%), and other bio-based materials (3%).

The remaining hotspots are associated with energy use (17%), broken down into 9% from electricity, 5% from heat, and 3% from fossil fuels, while infrastructure accounts for 2% of the total.

In the **woodworking sector**, the analysis of 142 datasets revealed that the majority of processes present environmental hotspots related to climate change (135 processes), fossil resource use (113 processes) and land use (76 processes). Other impact categories such as photochemical ozone formation, particulate matter, freshwater eutrophication, ozone depletion, acidification, and mineral resource use also frequently emerge as hotspots, though to a lesser extent, ranging from 60 to 18 processes. In contrast, terrestrial and marine eutrophication are identified as hotspots in only one process each, water use in two processes and ionizing radiation in four.

The main hotspot activities and flows are predominantly associated with the input of materials and chemicals, accounting for 62% of the total identified hotspots. Notably, 49% of these are related to wood inputs, of which 44% come from raw wood and 4% from semi-finished wood products such as particleboard and oriented strand board. The remaining 13% of material-related hotspots are linked to chemical inputs, primarily adhesives —including urea formaldehyde, phenolic resins, and melamine urea formaldehyde— as well as bio-based materials other than wood (2%), such as starch and vegetable oils, which are used in the production of fibreboards and during power sawing processes. Other frequent hotspots are associated with energy use, including 9% from electricity and 7% from fuels, mostly used for heating, wood chipping, and sawing operations. Additionally, transformation processes account for 22% of the hotspots, with 11% attributed to sawing and 9% to kiln drying, both of which are energy-intensive stages in wood processing.

In the **textile sector**, the most frequently identified environmental hotspots appear in the categories of climate change (26 processes) and acidification (25 processes), followed by particulate matter (19 processes), water use (17 processes), and fossil resource use (17 processes).

When analysing the inputs with the highest contribution to environmental impacts in terms of single-score process results, energy use stands out as the most significant, associated with 36% of the processes. Within this category, electricity accounts for 16% of the impacts, followed by heat at 10%, steam at 7% and diesel at 3%. Treatment activities, including upstream processes, come second, representing 25% of the identified hotspots. Within this group, the use of chemicals frequently emerges as a major contributor (19%), including substances such as surfactants, bleaching agents like hydrogen peroxide, and dye adsorption agents such as sodium sulphate.

Material inputs contribute 16% of the total impact. Specifically, the production of fibres from flax, jute, kenaf, cotton, and reeled raw silk accounts for 9%, while the production of yarn from jute, kenaf, cotton, and silk represents 7%. Additionally, both agriculture and wastewater management each account for 8% of the environmental hotspots, while water consumption represents 7%. It is worth highlighting that wastewater is the only category identified as a positive hotspot. This is because the wastewater flows undergo further treatment before being released back into natural water bodies, meaning that they do not exert a negative environmental impact at the point of re-emission.

In the **pulp and paper sector**, all 39 characterized processes show environmental hotspots in the categories of climate change, fossil resource use, and particulate matter. Moreover, 35 processes are also hotspots for acidification. Other impact categories that frequently emerge as hotspots include land use (28 processes), photochemical ozone formation (24), and water use (20), followed by mineral resource use, identified in 14 processes. On the other hand, terrestrial and freshwater ecotoxicity, ionizing radiation and ozone depletion were not identified as potential hotspots in this sector.

Material input is again the primary activity contributing to environmental impacts in this sector, linked to 65% of the processes. This is largely due to the use of chemicals and additives (17%), which are widely used in paper production for various purposes such as altering colour or strength, as well as in pulping, bleaching, and coating. Wood extraction also appears frequently as a hotspot (17%), mainly because of land use and fossil resource consumption associated with forestry operations. Other significant material inputs include paper and board production (11%), pulp production (7%), and starch (7%), which is an essential adhesive and bonding agent. Additional materials such as aluminium, latex, kaolin, and polyethylene —including packaging— collectively account for 5% of material-related impacts.

Energy use constitutes 24% of the identified environmental hotspots in this sector. Of these, 11% come from fossil energy sources, while 3% are linked to heat or power derived from biomass inputs such as wood chips, lignite briquettes and peat. Infrastructure, particularly pulp and paper mills, accounts for 5% of the hotspots. Transport, including delivery by lorry, train, and barge, contributes 4%, and municipal sludge waste, primarily associated with the production of containerboard and kraft paper, adds another 2%.

Finally, in the **biochemical sector**, 38 processes representing the production of biochemicals were characterized. Among these, climate change was identified as a hotspot in all processes, followed by particulate matter in 35 processes, acidification in 34, and fossil resource use in 32. In contrast, three impact categories did not emerge as hotspots: freshwater eutrophication, human toxicity (cancer), and ionizing radiation, suggesting that these categories are not likely to be major environmental concerns in the context of biochemicals.

In terms of contributing activities, material input accounts for the highest share of environmental hotspots, with 80% of the processes affected. Within this activity, biomass inputs represent 49% of the hotspots, encompassing both raw biomass and transformed materials such as wood chips and vegetable oils. Additionally, by-products from the pulp and paper industry and fatty acids make up 31% of the identified hotspot flows. Energy use is the second most significant activity, responsible for 9% of the impacts, particularly related to heat. This is followed by infrastructure and transport, each contributing 5%, and other activities, including the treatment of tallow to esterquat, which account for 1%.

3 SUSTAINABILITY PERFORMANCE BARRIERS IN THE CALIMERO PROJECT

Sustainability performance barriers refer to obstacles that hinder or prevent the effective implementation of sustainability initiatives. Examples of such barriers include high initial investment costs for sustainable technologies, inadequate infrastructure, and the absence of supportive policies or regulations that fail to incentivize sustainable behaviour or penalize unsustainable practices.

3.1 Sustainability performance barriers in the construction industry

The construction industry plays a fundamental role in sustainability impacts due to its high resource consumption, waste generation and contribution to carbon emissions (Kiani Mavi et al., 2021). To transition to more sustainable practices, the sector must reduce its dependency on natural resources and minimizing waste generation. The reuse of materials, recycling of construction waste and adoption of low-impact materials are key strategies to mitigate environmental effects (Sakthibala et al., 2025). Additionally, designing for disassembly and incorporating closed-loop strategies can facilitate material recovery at the end of a building's life cycle.

In terms of energy efficiency and carbon reduction, the industry must prioritize passive design strategies, the use of renewable energy sources, and the optimization of construction processes to minimize energy consumption throughout a building's life cycle (Mostafavi et al., 2021). Reducing embodied carbon in construction materials through more efficient manufacturing processes and selecting lower-impact materials is essential for aligning with the European Green Deal and other sustainability regulations.

To enhance its sustainability performance, it is essential to implement methodologies such as LCSA and PEF for enabling the evaluation of environmental, social and economic impacts of construction materials and processes, facilitating decision-making based on sustainability criteria (Backes & Traverso, 2021). One of the main challenges is the need to adopt a comprehensive life cycle assessment at all stages of the construction process, from raw material extraction to demolition and material reuse. Currently, the lack of standardization in the application of LCSA and PEF makes it difficult to compare results and identify high-impact processes, limiting their effectiveness (Scherz et al., 2022). To overcome this barrier, it is crucial to improve the availability and quality of data, promoting transparency in environmental information related to construction.

Another key aspect concerns regulatory harmonization and environmental certifications. The coexistence of multiple certification schemes, such as LEED, BREEAM and DGNB, can create confusion in the market (Parekh, 2024). Therefore, integrating LCSA and PEF approaches within these standards is essential to ensure a consistent sustainability assessment framework. Moreover, compliance with European regulations, such as the Energy Performance Buildings Directive (EPBD) and the EU Taxonomy is key to aligning projects with environmental goals and ensuring financial viability for sustainable investments.

Several specific needs and barriers were also identified during the implementation of the CALIMERO project. These include a complex interplay of technical, economic, institutional, and cultural challenges when transitioning toward a circular economy.

From a technical perspective, the heterogeneity of building designs, long lifespans, and the challenge of designing for deconstruction complicate the reuse or valorisation of components. Many existing buildings were not designed with disassembly in mind, making material recovery interventions (e.g. insulation, framework, composites) costly or unfeasible. In parallel, the lack of standardized metrics and certification for novel bio-based materials (e.g. stabilized BioChar, mineral ash admixtures, bio-oil derivatives) limits trust and market acceptance, especially when combined with uncertainties in durability, fire resistance, moisture interactions, and long-term performance. These technical uncertainties raise perceived risks for developers, insurers, and asset owners, inhibiting adoption.

From an economic perspective, circular bio-based solutions often require higher upfront capital investment (for pyrolysis units, ash recovery systems, feedstock preprocessing, quality assurance) and fragmented return streams (co-products, credits) rather than straightforward sellable outputs. Price volatility in conventional materials and weak economic incentives (such as carbon pricing or subsidies) further undermine the business case for circular materials. Institutional and regulatory inertia exacerbates the challenge, as procurement practices frequently prioritize the lowest-cost, well-established materials. In addition, existing codes, standards, and building regulations often fail to recognize bio-based or recycled inputs, while public clients may lack procurement frameworks that support circular models. Meanwhile, stakeholder fragmentation —many actors (architects, contractors, material suppliers, waste management) each with limited incentive to internalize life-cycle value— leads to coordination failure.

Lastly, cultural resistance plays significant role. Unfamiliarity and scepticism toward novel materials, reluctance to accept performance trade-offs, and path dependence on linear supply chains slow adoption. Several reviews emphasize that organizational and governance barriers predominate in architecture, engineering, and construction (AEC) circular economy adoption (Charef et al., 2021)

In the CALIMERO context, applying the BioChar valorisation pathway and waste cardboard feedstock intensifies certain barriers. These include the need for pyrolysis infrastructure within (or close to) building material facilities, the requirement to certify bio-oil or mineral ash use in building applications, and the necessity to manage a reverse logistics loop for used insulation products. In addition, because waste cardboard is less commonly used in high-performance building products than fibre board, its acceptance by material specifiers may be low —requiring extra quality testing, demonstration pilots, and standard inclusion. The innovations will also contend with incumbent suppliers holding entrenched market positions and limited willingness among clients to share risks in early deployments.

3.2 Sustainability performance barriers in the woodworking industry

The woodworking industry is one of the major industries in Europe, providing employment, supporting rural economies, and contributing to sustainable development through the use of a renewable resource. It covers the production of sawn timber, wood-based panels, and wood-based materials and products for construction. The latter, along with furniture, account for around 70% of wood used directly in the EU. In recent years, there has been renewed interest in wood products, driven by growing awareness of wood's role as a carbon sink and its favourable technological properties, particularly its high strength-to-weight ratio (Romagnoli et al., 2019). However, as demand for wood-based products continues to rise, the industry faces several challenges in achieving sustainability performance, including supply chain disruptions and shifting consumer preferences.

One of the main challenges for the woodworking and broader forest-based industries is the growing demand for wood. These sectors are under increasing pressure to adopt practices that ensure sustainable production, processing, and sales in order to avoid forest degradation and deforestation. In response, the European Union introduced the EU Deforestation Regulation (EUDR) in June 2023, with an 18-month transition period to support compliance. Additionally, access to affordable wood remains uncertain, particularly in regions where the bioenergy sector benefits from subsidies and competes for the same raw materials. This competition is expected to intensify as emerging bio-based industries increase their demand for wood as a feedstock (European Commission, 2025)

The woodworking sector can only offset high material and energy costs through high labour productivity. However, the workforce is aging, and young people show limited interest in joining the sector. To maintain productivity, it is crucial to attract new talent, equip workers with current competencies, and provide training in emerging technologies and high-tech processes.

From an end-of-life perspective, extending the durability and recyclability of wood products remains a major challenge (Zhang et al., 2023). While wood is valued as a natural and renewable material, customers also demand long-lasting products with strong mechanical performance, ease of maintenance, and stability over time. Unlike other materials, the suitability of wood for specific applications depends heavily on environmental conditions (i.e., in high-humidity settings, wood is susceptible to biotic degradation). Therefore, one of the main goals of wood technology research is to improve the technological performance of wood products — especially in relation to biodegradability— by optimizing the treatments, coatings, and adhesives used in manufacturing. These advancements aim to enhance durability while maintaining environmental sustainability (Romagnoli et al., 2019). Moreover, the processes of cutting, sanding, and assembly generate significant waste, which is not always reused or recycled efficiently.

Another important barrier is company size. Larger firms typically have greater financial and human resources to implement sustainability initiatives. In contrast, small and medium-sized enterprises (SMEs), which dominate the woodworking sector (with the exception of the wood-based panels sub-sector), face greater obstacles. These include limited access to capital, a lack of awareness of the business benefits of sustainable practices, and resource constraints in terms of time, money, and knowledge (Clark, 2012). Although many SMEs employ energy-efficient technologies, these may still fall short of meeting evolving sustainability standards, particularly with regard to electricity consumption (Macak et al., 2020).

Finally, the use of adhesives in wood-based composites is a significant environmental, economic, and social hotspot. Most conventional adhesives are made from non-renewable raw materials and emit toxic substances during production and use. Workers are often directly exposed to hazardous chemicals, contributing to occupational health risks such as respiratory problems and long-term exposure to carcinogens. Indoor air pollution, particle emissions, and insufficient safety measures also present notable social risks (Barclays, 2015; Marting Vidaurre et al., 2020). Replacing conventional adhesives —especially those based on formaldehyde— with safer, affordable alternatives remains a major challenge for the industry. Developing and scaling up these alternatives is crucial to improving the environmental footprint of wood-based products without compromising performance or accessibility.

3.3 Sustainability performance barriers the textiles industry

The textile industry is one of the most resource-intensive sectors, with a substantial environmental footprint across its supply chain. From raw material extraction to manufacturing, distribution and disposal, the industry faces significant challenges related to resource consumption, waste generation, chemical pollution and carbon emissions (Leal Filho et al., 2024). Related to this is the over-reliance on non-renewable and high impact raw materials, as synthetic fibres such as polyester dominate the market but are derived from fossil fuels and contribute to microplastic pollution in water systems. Even though there are natural fibres like cotton, which are biodegradable, they are related to high water consumption and pesticide usage (Gonzalez et al., 2023). Thus, sustainable alternatives (e.g., organic cotton, hemp, recycled fibres) must be scaled up in order to meet more sustainable practices, and this sustainability verified through transparent Life Cycle Assessment (LCA) methodologies. However, accessibility, affordability and scalability remain key barriers to widespread adoption of LCA.

Beyond raw materials, production is intensive in terms of energy (Farhana et al., 2022), for instance for the dyeing or synthetic fibre processing, which often rely on fossil fuels. The widespread use of toxic chemicals in e.g., dyeing and other treatments leads to significant water pollution, especially in regions with weak environmental regulations. Consequently, transition to low-impact dyeing technologies, safer chemicals, water-efficient processes, and renewable energy sources can significantly reduce the industry footprint.

Improving the recyclability and waste management practices is another urgent matter, as the textile industry generally follows a linear economy model (Stella et al., 2024). This is illustrated by fast fashion, that exacerbates the problem by promoting short-lived products quickly ending up in landfills or incinerators. Thus, implementing circular economy strategies is essential for addressing this issue, focusing on longer-lasting products, textile recycling, upcycling and extended producer responsibility schemes.

The social dimension of sustainability in the textile industry, especially for fast fashion, is equally critical (Fidan et al., 2024). Labor-intensive production in low-cost manufacturing countries often involves exploitative conditions, including low wages, unsafe working environments and, in some cases, human rights violations. Consequently, strengthening supply chain transparency, and engaging in fair labour practices and ethical sourcing initiatives is fundamental to ensuring that sustainability efforts extend beyond environmental concerns.

In this regard, consumer awareness and regulatory enforcement can play a major role pushing brands toward responsible sourcing and ethical production. Improving the traceability of chemicals and fibres used along supply chains is paramount to such efforts.

Regulatory alignment with EU sustainability policies is also crucial. The European Commission's Circular Economy Action Plan, the Strategy for Sustainable and Circular Textiles, the Waste Framework Directive, and the Green Claims Initiative are driven by the need for some of the aforementioned industry reforms. In line with this, integrating PEF methodologies into product development will enhance transparency, helping consumers make informed purchased decisions based on environmental impact. Organisations must thus prepare for stricter regulations on eco-design, greenwashing prevention and waste management in the near future.

Finally, improving the sustainability of textile industries require a solid, scientifically valid approach, supporting the implementation of sound policies and regulations. The uptake of these methodologies, policies and regulations by the industry, and the display of transparent and accurate social and environmental information to consumers, are key enablers to improve the sustainability of the textile industry. Currently, this is impeded by the limited knowledge of complex, multitier global supply chains, the quality and representativity of available data, and the proper assessment of environmental and socio-economic impacts.

3.4 Sustainability performance barriers in the pulp and paper industry

The pulp and paper industry has a relevant role in Europe's economy but also presents significant sustainability challenges due to its high water and energy consumption, deforestation risks, and emissions from chemical processing (Johansson et al., 2021). While the sector has made strides in improving its environmental footprint, key areas still require attention to align more sustainable practices, such as raw material sourcing, water and energy use, and waste generation, among others.

A major challenge within the pulp and paper industry is the high demand for wood, which makes it one of the main drivers of forest loss and deforestation of both natural and plantation forests. From 1700 to 2020, the world has lost 1.5 billion hectares of forest with deforestation rates peaking in the 1980s. However, although the rates have declined since the 1980s, the net loss remains significant with on average 4.7 million hectares per year between 2010 and 2020. Approximately 95% of global deforestation occurs in tropical regions, with Latin America and Southeast Asia being the most affected regions (Our World in Data, 2023). Deforestation contributes significantly to global CO_2 emissions, with estimations of contributing to around 10% of global anthropogenic GHG emissions (IPCC, 2019; FAO, 2023). Apart from generating GHG emissions, environmental concerns also include loss of natural habitat leading to biodiversity loss and species extinction and soil erosion.

In this context, although Europe has strong forest management regulations, ensuring a sustainable and traceable supply chain remains critical to preventing biodiversity loss and ecosystem degradation. Expanding the use of certified wood fibres (FSC, PEFC) and recycled paper can reduce dependence on virgin materials while promoting circularity. However, improving fibre recovery rates and enhancing the efficiency of recycling processes remain ongoing challenges (Pihkola et al., 2024).

Another critical aspect is the sector's energy intensity. the pulp and paper sector is among the top five most energy-intensive industries globally, accounting for approximately 6% of global industrial energy use and 2% of direct industrial CO_2 emissions (Del Río et al., 2022). Much of the energy comes from burning biomass, but fossil resources are also used especially in the papermaking. The use of energy from fossil resources in the pulp and paper production has environmental implications and is an important issue for the sector. Since the 1990s, the industry has conducted significant environmental improvement such as and energy management systems and ecolabelling initiatives. However, continued efforts are needed to further decarbonize production. Historically, emissions to air have been a huge problem, where sulphur emissions from pulp production, has contributed to acidification. However, the sulphur emissions have been reduced due to process technology improvements and efforts to not exceed critical air pollutions levels are of importance for mills in Europe (Suhr et al., 2015).

Chemical use also represents an important environmental hotspot, both in terms of production and emissions to water bodies. Despite improvements over time, high water flow still leads to substantial effluent volumes containing contaminants such as EDTA and nutrients (nitrogen and phosphorus) contributing to eutrophication, and suspended solid (Suhr et al., 2015). Regarding the water use, water recirculation techniques have been developed to decrease the net freshwater usage. Further reduction of water use is essential for regions with scarce water resources or a dry climate (Suhr et al., 2015).

Waste generation poses another major sustainability concern. The pulp and paper industry is estimated to account for up to 40% of global municipal solid waste. Recycling of paper waste has therefore been highlighted as a top priority within the sector. Globally, around 50% of waste paper is recycled, with numbers being higher in Europe with around 72% of all paper waste and over 80% of paper boards being recycled (Del Río et al., 2022).

In the case of tissue production, which is typically a single-use product, increasing the share of recycled fibre input or using alternative fibres such as wheat straw could further enhance circularity. However, the decreasing availability of paper for recycling —due to declining newspaper and graphic paper consumption— represents a growing barrier for the tissue sector.

For addressing these needs, waste reduction and circularity present a major opportunity. While paper is highly recyclable, contamination, fibre degradation, and logistical inefficiencies limit the full potential of recycling systems, but by strengthening eco-design principles, reducing the use of non-recyclable coatings, and improving waste collection infrastructure extending the life cycle of paper products could be achieved.

3.5 Sustainability performance barriers in the biochemical industry

The European biochemical industry is essential for developing bio-based alternatives to fossil-derived chemicals, but it faces challenges related to resource efficiency, raw material sustainability, and production emissions. Even though bio-based chemicals can reduce reliance on petroleum, a primary concern is the sourcing of biomass feedstocks as unsustainable agricultural or forestry practices can lead to land-use change, biodiversity loss, and water depletion. Strengthening certified and waste-based feedstock use, along with improving traceability, is critical for sustainability (Moutousidi & Kookos, 2021).

Energy and water consumption during bioprocessing are also under scope. Enhancing process efficiency, utilizing renewable energy, and implementing closed-loop water systems can significantly lower environmental impact. Additionally, managing by-products and waste streams through circular economy approaches will improve resource efficiency.

In the context of biochemicals production, environmental hotspots can result from the agricultural phase, and the use of chemicals and energy-intensive processes that release pollutants into the environment. These pollutants can lead to a range of adverse environmental impacts such as water and air pollution, habitat destruction, and loss of biodiversity. Biochemicals, which are produced from renewable biomass sources, have been promoted as a more sustainable alternative to fossil-based chemicals. However, producing biochemicals on a large scale poses significant environmental challenges. Biochemical production processes require large amounts of water, energy, and chemicals, which can lead to the release of GHGs and other harmful pollutants.

Moreover, the agricultural practices required to produce the biomass feedstocks can result in land-use change, deforestation, and loss of wildlife habitat. To mitigate the negative environmental impacts associated with the production of biochemicals, several strategies can be employed. These include the use of more efficient production processes, reducing the amount of waste produced, and implementing sustainable feedstock production practices. Additionally, the development of a circular economy approach, where waste products are recycled and reused, can further reduce the environmental impact of biochemical production (Ögmundarson et al., 2020a, 2020b).

The most important and abundant biochemical production in the world and in Europe is bioethanol which about 80% of that is from fermentation of food commodities (e.g., sugarcane and corn), causing significant environmental burdens on agricultural practices. Hence, using of organic wastes and conversion of them to bioethanol can mitigate GHG emissions while providing a sustainable and eco-friendly method for waste disposal. Therefore, the adoption of environmentally friendly production practices is crucial in ensuring that the transition to renewable biochemicals does not result in the creation of new environmental hotspots (Obydenkova et al., 2022).

3.6 Cross-sectorial barriers

Across the CALIMERO bio-based sectors, several cross-cutting barriers limit stakeholders' ability to assess, compare and improve sustainability performance. A central challenge concerns the availability, quality and representativity of Life Cycle Inventory (LCI) data. Collecting reliable data for LCA is time-consuming, particularly when multiple processes and suppliers are involved (**D1.2**). While existing databases generally capture major environmental hotspots, significant gaps remain for emerging bio-based products and innovative processing routes, including production steps and end-of-life scenarios such as recycling and landfilling. The geographic representativity of environmental data is often limited, and traceability beyond tier-1 suppliers is low, reducing the reliability of assessments. Similarly, data on chemicals used across processes are often generic, which may underestimate environmental and social impacts.

Social and economic data limitations were also observed. Social databases tend to be generic and poorly representative of specific supply chains or processes, leading to discrepancies between database information and actual social issues managed by stakeholders (Muñoz-Torres et al., 2023). Economic databases covering supply chain contributions, regional socio-economic performance, or value-added distribution among stakeholders are largely absent. Greater availability of such data could improve policymaking, support fair Extended Producer Responsibility (EPR) schemes under the EU Waste Framework Directive, and enable stakeholders to identify hotspots early and prioritize data collection.

Life Cycle Impact Assessment (LCIA) methodologies also present barriers. Existing methods are insufficient to fully capture impacts on land use, biodiversity, and dynamic carbon flows, particularly for bio-based materials (**D1.3**). Inconsistencies in normalization, weighting, and system boundaries reduce comparability between studies and hinder effective benchmarking across sectors.

Beyond these data and methodological gaps, additional barriers identified in **D1.4** affecting all sectors include:

- Limited internal expertise or resources to perform or interpret sustainability studies, which are often complex, costly, and conveyed in technical reports not easily accessible to untrained personnel. In addition, process optimization sometimes must rely on multi-criteria and multi-parameter process simulations to identify the best solutions, which requires tailored models and specific technical competences for the modelling (**D2.2**).

- Inconsistencies between sustainability assessment methodologies, including functional units, temporal and technological boundaries, and weighting approaches, which reduce comparability and reusability.

- Low motivation of indirect (financial sector) and direct (industries) actors to invest into industrial innovation, transformation or technologies increasing sustainability. This is particularly the case for industrial actors when investments are not clearly linked to process optimisation and associated cost reductions. This is exacerbated by the volatile price of raw materials and commodities, which makes it difficult to identify the most effective pathway to increased sustainability.

- Divergent stakeholder perspectives, which complicate the development of harmonized approaches for sector transformation.
- Past greenwashing practices associated with bio-based alternatives (e.g., claiming the product is eco-friendly solely because it is bio-based or compostable), may have had a significant negative impact on consumer trust and on the image and brands of companies that did so. This may lower the uptake of truly sustainable bio-based products in the market.
- Consumer trust and access to transparent information: the lack of standardized methodologies and indicators, combined with the inconsistent terminology used by the bio-based sectors, lack of transparency, consumers' misconceptions about bio-based materials, and inconsistent environmental sustainability reporting, significantly impact consumer decision-making.

4 SUSTAINABILITY PERFORMANCE GUIDELINES & RECOMMENDATIONS ACCORDING TO CALIMERO FINDINGS

4.1 Sustainability performance opportunities in the construction industry

Despite the barriers, the construction sector offers unique leverage points for embedding circular bio-economy principles, especially through integrated material, design, and systems innovations:

- The BioChar valorisation route transforms post-use cellulose insulation into a carbon-storing product while generating valuable co-outputs (bio-oil, minerals) that can substitute conventional feedstocks in adjacent industries (e.g., agriculture). This cascading use closes loops across organic and inorganic flows, improves resource efficiency, and reduces demand for virgin minerals. Recovering mineral additives from ash converts what was once waste into "new raw material," lowering criticality and supply risk.
- Substituting waste cardboard (instead of premium recycled paper) as a feedstock. This provides a more abundant, lower-competition resource stream, enabling scalable circular feedstock flows without interfering with fibre recycling loops. Cardboard's wide availability, lower quality sensitivity, and regional dispersion support resilient, distributed collection systems, strengthening local circular economies
- Integrating BioChar into insulation can offer the potential for a net negative carbon balance by storing stable carbon while avoiding incineration or landfill emissions. Optimized pyrolysis and logistics systems, combined with renewable energy use, enhance cumulative carbon benefits over repeated cycles. Additionally, co-product streams and avoided disposal costs generate revenue or offsets that improve the life cycle cost profile.
- Modular and reversible design enabled by circular construction principles —such as design for deconstruction, modular panels, and material passports— allows buildings and components to be adapted, reused, and revalorised rather than demolished. This extends material lifespans, reduces embodied carbon, and benefits from policy support (EU circular economy action plan, EU taxonomy, green procurement, potential carbon storage subsidies) alongside growing market demand for low-embodied-carbon building products. Circular construction also creates opportunities for local employment in feedstock collection, pyrolysis, material recovery, reverse logistics, testing, and certification, supporting regional economic development, especially in areas with under-utilised waste

cardboard streams or emerging bioproduct capacities.

4.2 Sustainability performance opportunities in the woodworking industry

Based on the hotspots and challenges identified, there are several opportunities and potential solutions to improve sustainability performance in the woodworking sector:

- Use of wood certified under programs such as PEFC (Programme for the Endorsement of Forest Certification) or FSC (Forest Stewardship Council) to enhancs the sustainability of the supply chain. These certifications promote responsible forest management, biodiversity conservation, water quality protection, and sustainable harvesting practices, while also increasing market credibility and consumer trust.

- The integration of automation, artificial intelligence (AI), and digital monitoring systems can significantly enhance production efficiency. These technologies help reduce material waste, optimize energy use, and improve quality control.

- Reusing internally collected wood waste, such as trimmings, dust, and rejected panels, as raw material for new products or for energy generation. This reduces landfill waste, minimizes the demand for virgin resources, and lowers production costs.

- Selecting resins with a low free-formaldehyde content and applying optimal pressing conditions (temperature, pressure, and time) in order to reduce harmful emissions during production.

- To minimize air emissions from dryers and presses, companies can adopt one or a combination of BATs described in the BAT Reference Document (BREF) for the wood-based panel industry. Examples include bag filters, wet scrubbers, and wet electrostatic precipitators, which effectively control particulate matter and volatile organic compound (VOC) emissions.

- Investing in training programmes focused on sustainable environmental practices and digital skills can help maintain competitiveness and attract young talent to the sector.

- Upgrading machinery to more energy-efficient models and integrating renewable energy sources (e.g. biomass boilers, solar panels) into operations can reduce greenhouse gas emissions and energy costs in the sector.

- Application of eco-design principles during product development extends the product's lifespan and improves its recyclability at the end of its life.

4.3 Sustainability performance opportunities the textiles industry

The textile industry can improve its practices in multiple ways, several of which were identified during the CALIMERO project (see in particular, **D1.4**):

- Implement targeted process simulation or Multi-Objective Optimization (MOO) approaches, early in the product development stage to guide decision-making from the design phase. These approaches can be tailored to address known impact hotspots (e.g., water, energy, and chemical consumption) offering opportunities to reduce associated environmental impacts.

- Shift to more sustainable and traceable feedstocks, encouraging key suppliers to adopt transparent and sustainable practices. Social aspects should also be considered, including fair labour conditions and worker wellbeing throughout the supply chain. Digital Product Passports (DPPs) present an opportunity to integrate these aspects into industry practices while enhancing transparency and communication with both B2B and end consumers.

- Ensure that no harmful or toxic (e.g., by REACH regulation) chemicals are present in the feedstock or products.
- Design products for durability, repairability, and recyclability to promote circular practices, potentially enhancing brand reputation and improving the industry's overall image.
- Reduce overproduction, particularly in fast fashion, and foster a more local and quality-controlled textile industry within the EU. This approach can improve product quality, encourage consumer preference for locally produced goods, and generate additional employment and income opportunities within the region.

4.4 Sustainability performance opportunities in the pulp and paper industry

A range of opportunities to improve sustainability performance in the pulp and paper industry are summarized below, based on previously identified challenges.

- Ensure responsible sourcing of wood, taking into consideration both environmental as well as economic and social impacts. Several certification schemes exist such as the Forest Stewardship Council (FSC), as well as the Programme for the Endorsement of Forest Certification (PEFC).
- Reduction of water use through techniques such as water recirculation, which can significantly decrease the net freshwater usage by the pulp and paper mills in regions with scarce water resources or a dry climate (Suhr et al., 2015).
- Enhance energy efficiency by focusing on reducing energy consumption in production, replacing outdated, low-efficiency equipment with modern upgrades, and adopting sustainable energy sources, such as bio-based energy, in place of fossil fuels.
- Improve the process technology for boilers, since boiler are the major source of GHG emissions, SO_2, NO_x and particulate matter in the sector. In Sweden, many mills employ bio-based energy source alternatives instead fossil-based (Del Río et al., 2022).
- Optimize the paper drying process by improving energy efficiency and integrating renewable energy sources (Del Río et al., 2022).
- Increase recycling of pulp and paper products, which not only reduces waste but also opens opportunities for industrial symbiosis with other sectors. Waste streams from pulp and paper production can serve as feedstocks for industries such as biochemicals and metallurgy (Pieter le Roux et al., 2024).
- Valorise pulp ash waste generated during combustion processes. Instead of sending it to landfills, innovative approaches suggest its use in industrial symbiosis with the construction sector. For example, using pulp ash as a partial substitute (up to 10%) in concrete production can reduce landfill disposal and contribute to decarbonizing construction materials through material substitution (Ahmad et al., 2023).

4.5 Sustainability performance opportunities in the biochemical industry

Potential solutions to reduce environmental impacts associated with the production of biochemicals include the use of more efficient production processes, reducing the amount of waste produced, and implementing sustainable feedstock production practices. More detailed recommendations are present below:

- Development of a circular economy approach, where waste products are recycled and reused, can further reduce the environmental impact of biochemical production (Ögmundarson et al., 2020a, 2020b).
- Use bio-based sources in ester production instead of fossil-based substrates, as the bio-based production utilizes renewable resources like plant-derived feedstocks (Obydenkova et al., 2022). These plants absorb CO_2 from the atmosphere during their growth, which offsets the carbon emissions released during the production process.
- Transition to bio-based ethylene oxide for PEG production, derived from bioethanol produced from biomass or woodworking residues. By utilizing these bio-based resources, the production of PEG can significantly reduce dependency on fossil fuels while growing a cross-sectoral synergy between the bio-chemical and wood-working sectors (Soleymani Angili et al., 2021; Zanon-Zotin et al., 2023).
- Integrate bio-based raw materials via industrial symbiosis. One key opportunity is in replacing fossil-based carboxylic acids with tall oil, a by-product of the pulp and paper industry. Tall oil is obtained during the kraft pulping process, where cellulose fibres are separated from lignin in wood. This complex mixture, rich in fatty acids and resin acids, presents a valuable alternative to fossil-derived chemicals in the esterification process. By utilizing tall oil, the bio-chemical sector not only reduces reliance on non-renewable resources but also strengthens cross-sector collaboration, particularly with the pulp and paper industry. To ensure its suitability for ester production, crude tall oil (CTO) undergoes refining to remove impurities and optimize its composition. This refined bio-based carboxylic acid can then be directly used in esterification, aligning with circular economy principles while reducing environmental impact (Cashman et al., 2016).
- Produce biochemicals from organic waste, for example, adipic acid, which is typically derived from fossil sources. Producing adipic acid through bioprocessing routes appears promising as it not only eliminates N_2O emissions, but also enhances the use of renewable resources such as biomass, instead of fossil feedstocks. Forest residues, primarily composed of branches and tops from commercial thinning, can be considered a promising renewable resource (Aryapratama and Janssen, 2017).
- Enhance textile recycling with bio-based solvents and chemicals, enabling eco-friendly dye stripping, elastane removal, and fibre regeneration. This creates synergy between biochemical and textile sectors, improves recyclability of blended fabrics, and reduces reliance on fossil-derived input (Hammar et al., 2023; Michud et all, 2016).
- Within the BAT reference document for the Production of Large Volume Organic Chemicals (Falcke et al., 2017) relevant BATs related to ester production were identified. These include:
    - Use efficient catalysts to reduce by-products and enhance reaction yields.
    - Recover thermal energy using heat exchangers, lowering external energy requirements.
    - Utilize by-products within processes or convert them into valuable secondary products.
    - Design closed-loop systems to recycle solvents and other materials internally.
- Implement BAT solutions for ethylene oxide and ethylene glycol production to reduce emissions and improve resource efficiency:

  - Use oxygen instead of air in ethylene oxidation to reduce CO_2 and organic pollutants.
  - Recover energy and minimize VOC emissions with techniques such as Pressure Swing Adsorption, membrane separation, catalytic oxidation, or thermal oxidation.
  - Improve energy efficiency using heat recovery from process streams.
  - Implement effective waste management, including by-product recovery, reuse, and treatment to reduce environmental impact before disposal or discharge.

4.6 Cross-sectorial opportunities

Based on the cross-sectoral barriers and data gaps identified in the CALIMERO project, there are several opportunities to improve sustainability performance across all bio-based sectors:

- Expanding environmental, social, and economic databases to cover missing processes, materials, chemicals, and end-of-life scenarios, while improving regional representativity.
- Implementing traceability tools, such as blockchain, and engaging suppliers to ensure more consistent and reliable data along multi-tier supply chains.
- Implement improved LCIA methodologies to better assess toxicity, dynamic carbon footprints, land-use impacts, and circularity indicators (CALIMERO WP3), while harmonizing normalization and weighting across studies.
- Developing user-friendly, open-access process simulation and MOO tools to support data-driven process and product optimization.
- Enhancing corporate transparency and consumer communication through clear, standardized sustainability indicators and reporting on supply chains and environmental/social performance.
- Promoting collaboration and knowledge sharing among stakeholders to accelerate the adoption of harmonized methodologies and best practices across sectors.

5 CONCLUSIONS AND FURTHER STEPS

The analysis of the five bio-based sectors within the CALIMERO project shows that environmental hotspots are mainly driven by material inputs and energy use, with sector-specific challenges. In construction, high resource consumption, waste generation, and embodied carbon emissions demand a transition toward circular practices such as material reuse, recycling, and design for disassembly, alongside improved energy efficiency through passive design and renewable energy integration. In woodworking, the high demand for wood risks forest degradation and deforestation, while extending the durability and recyclability of wood products remains a challenge. In textiles, energy-intensive production, water consumption, and chemical use dominate impacts, alongside critical issues in circularity, supply chain transparency, and labour conditions in low-cost manufacturing regions. The pulp and paper sector faces pressures from wood sourcing (as in woodworking), chemical use, and waste generation, particularly in single-use products such as tissue, highlighting the need for recycled inputs and alternative fibres. Biochemical production, despite relying on renewable biomass, experiences significant environmental pressures from feedstock sourcing, chemical inputs, and energy-intensive processes, including agricultural impacts and pollutant emissions.

For all of the sectors several opportunities and potential solutions to improve sustainability performance were proposed. Collectively, these measures will contribute to a more sustainable, circular, and resilient bio-based industry, ensuring that the transition to renewable materials does not create new environmental hotspots while supporting economic and social value creation.

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