Ref. Ares(2025)9166608 - 27/10/2025

CALiMERO

IMPROVING BIO-BASED INDUSTRIES LIFE CYCLE SUSTAINABILITY

D5.6

Guidelines and recommendations to develop PEF and PEFCRs

Due date of submission: 31/10/2025

Actual submission date: 27/10/2025

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Contents

List of acronyms

AAM	Advanced Air Mobility	**IAM**	Innovative Air Mobility
c-PCR	complement PCR	**ISO**	Internation Standardization Organization
D	Deliverable	**LCA**	Life Cycle Assessment
DDS	Due Diligence System	**LCC**	Life Cycle Costing
EDA	European Dairy Association	**LCSA**	Life Cycle Sustainability Assessment
EASA	European Union Aviation Safety Agency	**OEF**	Organization Environmental Footprint
EFA	Environmental Footprint Aviation	**OEFSR**	OEF Sector Rule
EMEA	Europe, the Middle East and Africa	**OELs**	Occupational Exposure Limits
ESTC	EMEA Synthetic Turf Council	**PEF**	Product Environmental Footprint
EF	Environmental Footprint	**PEFC**	Program for the Endorsement of Forest Certification
EU	European Union	**PECR**	PEF Category Rule
EUDR	EU Deforestation-free Regulation	**S-LCA**	Social Life Cycle Assessment
FEDIAF	European Pet Food Industry Federation	**UAM**	Urban Air Mobility
FEFAC	European Feed Manufacturers Federation	**WP**	Work Package
FU	Functional Unit		

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PROJECT INFORMATION

Project full title: Industry CAse Studies AnaLysis To IMprove EnviROnmental Performance And Sustainability Of Bio-Based Industrial Processes

Acronym: CALIMERO

Call: HORIZON-CL6-2021-ZEROPOLLUTION-01

Topic: HORIZON-CL6-2021-ZEROPOLLUTION-01-06 - Increasing the environmental performance of industrial processes in bio-based sectors: construction, woodworking, textiles, pulp and paper and bio-chemicals

Start date: 1st July 2022

Duration: 48 months

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

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DELIVERABLE DETAILS

Document Number:	D5.6
Document Title:	Guidelines and recommendations to develop PEF and PEFCRs
Dissemination level	PU – Public
Period:	PR2
WP:	WP5
Task:	T5.5
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Abstract:	Bio-based industries play a key role in reducing dependence on fossil-based materials and promoting a circular and sustainable economy. However, the coverage of bio-based sectors by the Product Environmental Footprint (PEF)'s Category Rules (PEFCRs) is far from complete. So far, only some products such as food and feed (e.g. beer, pasta, dairy, pet food), ornamental agriculture (cut flowers and potted plants), and apparel and footwear are covered by recently developed or revised PEFCRs. This document analyses the current level of PEFCR applicability across five targeted bio-based sectors of the CALIMERO project (construction, textiles, woodworking, pulp and paper, and biochemicals). The report highlights key methodological limitations of the PEF framework, including insufficient coverage of biodiversity, toxicity, biogenic carbon accounting, and circular economy modelling. In response, CALIMERO proposes a set of short- and long-term recommendations to address these gaps and also other to go beyond PEF. These contributions aim to support the development of the PEF methodology and PEFCRs of bio-based systems.

Version	Date	Description
V1	27/10/2025	First version

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1 INTRODUCTION

1.1 Towards a standardization of life cycle approaches in a European context

Life cycle sustainability assessments (LCSA) aim to evaluate the potential sustainability impacts from human activities related to all life cycle stages of a process or product, from extraction of raw materials to end-of-life (i.e., by following a cradle-to-grave perspective), including manufacturing, distribution, and use. The evaluation allows identifying and quantifying the environmental, social, and economic burdens associated with each life-cycle stage. It is a practical instrument supporting the decision-making process, particularly in domains such as policy-making and business operations, although the overarching goal is to prevent the burden-shifting between the three sustainability pillars (i.e., environment, society and economy), apart from across different life cycle stages (Mazzi, 2020).

Methodologies and tools are used as evaluation processes to determine the sustainability impact in the case under study. In this regard, three different life cycle approaches have emerged depending on the sustainability dimension considered: Life Cycle Assessment (LCA), Social Life Cycle Assessment (S-LCA), and Life Cycle Costing (LCC) for the environmental, social, and economic impacts, respectively. Consequently, a LCSA is recommended to be followed when the objective is to address sustainability impacts in a holistic manner (Valdivia et al., 2021).

The assessment of environmental impacts by the LCA methodology is, by far, the most advanced and used method. This may have overshadowed socio-economic impacts, since the focus on environmental impacts has been a common practice in the literature over the last few decades (Hauschild et al., 2018). This applicability gap is partly caused by the fact that environmental LCA has for a long time been internationally standardized by ISO 14040 (ISO, 2006a) and ISO 14044 (ISO, 2006b), which respectively describe the principles and framework of LCA, as well as its requirements and guidelines. Recently, the ISO proposed the principles and framework for social life cycle assessment (ISO 14075) (ISO, 2024).

Furthermore, the LCA approach has been further delineated to a European standard through the implementation of the Product Environmental Footprint (PEF) methodology. The PEF was developed to provide a framework for the development of a harmonized European methodology for assessing the environmental performance of products and organizations, with the objective of enhancing consistency and reproducibility of results in comparison with existing methods (European Commission, 2013a). Subsequently, the guidelines for environmentally performing both products and organizations were materialized two years later in the form of PEF and Organization Environmental Footprint (OEF) Guidelines, which were collected in the EU Recommendation 2013/179/EU (European Commission, 2013b). This common method to measure and communicate the life cycle environmental performance of products and organizations was further refined by means of the PEF Category Rules (PEFCRs) and OEF Sector Rules (OEFSRs) during a five-year period (2013 – 2018) during the Environmental Footprint (EF) pilot phase, in which a 6.3 version was obtained (European Commission, 2018). All the results from the pilot phase were considered as potential improvements to be implemented during the transition phase. This initiative was initiated in 2019 and is currently ongoing, with an expected conclusion date of 2025. It involves the monitoring of existing PEFCRs and OEFSRs, the development of new ones, and advancements in methodology in conjunction with the integration of the latest scientific developments (European Commission, 2021).

1.2 Main aim and objectives

The primary objective of this document is to provide a series of guidelines and recommendations for the

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development of PEF and PEFCRs of five target sectors: (i) construction, (ii) woodworking, (iii) textiles, (iv) pulp and paper, and (v) biochemicals, in a bioeconomy context. In this regard, the guidelines and recommendations to be proposed are intended to support the Technical Secretariat (TS) members (industry representatives, NGOs, scientific experts, and government institutions) in refining the existing PEF guide and PEFCRs within the aforementioned bio-based sectors. To that end, a series of secondary objectives have been established, including:

- Conducting a review of the state-of-the-art of the implementation levels of the PEF method, with a particular focus on the PEFCRs that have been recently developed, in development, as well as those that are already developed or under revision.

- Providing an overview of the current implementation process of PEFCRs in a bioeconomy context both in a general and specific way for each of the five-target bio-based sectors of the CALIMERO project, identifying the associated methodological limitations.

- Compiling a series of practical recommendations to be implemented as potential improvements to the current PEF method.

- Exploring options to extend PEF beyond environmental LCA, i.e., including socio-economic aspects.

1.3 Report structure

Section 2 provides a detailed description of the PEFCRs. First, divided into three groups based on the stage of implementation: new, in development, and under revision (Section 2.1). Section 2.2 presents the current implementation status of the PEFCRs, focusing on the five sectors within the scope of the CALIMERO project. Section 3 summarizes the methodological gaps and limitations of the PEF methodology, particularly in key areas of concern for bio-based sectors. Section 4 highlights the contributions of CALIMERO in addressing these areas and offers recommendations for future iterations of the PEF method. It also identifies which general PEF recommendations should be prioritized for the CALIMERO sectors and subsequently included in the corresponding PEFCRs (Section 4.1). Finally, Section 5 presents the main conclusions.

2 PEFCRs Context and Relevance

2.1 Implementation status of the PEFCRs

As mentioned, PEFCRs provide sector-specific guidelines to ensure consistency, comparability, and reliability according to the PEF methodology. They can be categorized as new, in development or under revision.

New PEFCRs include apparel and footwear, cut flowers and potted plants, and synthetic turf. The **apparel and footwear** PEFCR cover the full life cycle from raw material sourcing, dyeing, and water consumption to microplastic release, durability, and end-of-life disposal. This PEFCR addresses fast fashion's environmental footprint and promotes circular fashion and eco-design strategies[1]. The **cut flowers and potted plants** PEFCRs, motivated through the FloriPEFCR project launched in 2020, provide sector-specific rules and a software tool to calculate environmental impacts from greenhouse production, transportation and resource use (Broekema et al., 2024). The **synthetic turf** PEFCR, promoted by the ESTC between 2019 and 2023, evaluates materials, production, installation

[1] https://pefapparelandfootwear.eu/

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and disposal of synthetic turf systems used in sports and landscaping, supported by a calculation tool to improve transparency and sustainability within the industry[2].

PEFCRs currently under development cover multiple emerging sectors. The **aviation, drones and eVTOLs** (electric Vertical Take-Off and Landing aircrafts) PEFCR, is being developed by EASA European Union Aviation Safety Agency) through the Environmental Footprint Aviation (EFA) methodology[3]. It aims to standardize environmental performance assessments across aircraft production, fuel consumption, and emissions. The **marine fish** PEFCR seeks to assess the environmental footprint of both wild-caught and farmed fish, including overfishing risks, feed sustainability, aquaculture energy use, and bycatch impacts. Although development was paused in 2016 due to data limitations, a draft PEFCR had already undergone public consultation and review by independent LCA experts appointed by the European Commission[4]. The **space sector** PEFCR will address satellite manufacturing, rocket emissions, sustainable materials, energy efficiency, and space debris management to support sustainable space activities. This project, starting in 2024 and expected to be finalized by 2027, supports environmentally sound space exploration and aligns with EU policies on clean technology innovation[5]. Additionally, the **tourism sector** PEFCR focuses on measuring the environmental footprint of hotel accommodations, accounting for room types, occupancy, utilities, in-room products, and cleaning services [6].

Several PEFCRs are currently under revision to align with the latest PEF methodology. The **beer** PEFCR, initially approved in 2018 but expired in 2021, is being updated by the Brewers of Europe to reduce emissions, improve energy efficiency, and promote low-impact packaging options[7]. The **dairy** PEFCR, promoted by the European Dairy Association, was updated to integrate climate-smart dairy farming approaches, enhanced biodiversity protection, and carbon sequestration strategies in dairy supply chains[8] (valid until December 2025). The **feed for food-producing animals** PEFCR is led by FEFAC (European Feed Manufacturers Federation), and a revision currently ongoing highlights alternative protein sources (e.g., insect-based and algae-based feed), circular feed systems, and regenerative agriculture practices[9]. The **pet food** PEFCR promoted by the FEDIAF (European Pet Food Industry Federation) and the revised PEFCR[10] explores sustainable protein sources (e.g., insect meal, plant-based alternatives), waste reduction in production, and improved recyclability of packaging materials. The **pasta** PEFCR, initiated by the Nordic Council of Ministers, integrates low-carbon agriculture, precision farming, and sustainable water use, though its finalization has stalled since 2016 due to data challenges and since then, there have been no public updates regarding the status[11]. Finally, the **batteries and accumulators** PEFCR which is led by RECHARGE (a European industry association for advanced rechargeable and lithium batteries) and the revision aims to incorporate updated sustainability criteria, particularly focusing on critical raw materials, carbon footprint reduction, recycling efficiency, and circular economy principles[12], as well as compliance with the EU Battery Regulation

2 https://www.estc.info/knowledge-centre/product-environmental-footprint/

3 https://www.easa.europa.eu/en/en/domains/drones-air-mobility/drones-air-mobility-landscape/noise-sustainability/sustainability-environmental-footprint

4 https://www.marinefishpefcr.eu/

5 https://defence-industry-space.ec.europa.eu/shape-sustainable-future-engage-development-pefcr-space-2024-09-18_en

6 https://pefhotelaccommodation.eu/

7 https://brewersofeurope.eu/a-communication-on-the-beer-product-environmental-footprint-category-rules-beer-pefcrs/

8 https://eda.euromilk.org/food-environment-health/sustainability-environment/dairy-product-environmental-foot-print/

9 https://fefac.eu/priorities/sustainability/pefcr-feed/

10 https://europeanpetfood.org/sustainability/product-environmental-footprint-category-rules-pefcr-for-pet-food/

11 https://www.nordic-pef.org/pasta-pef?utm_source

12 https://rechargebatteries.org/?s=PEFCR

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2.2 Applicability of the PEFCRs for the five-target industries in CALIMERO

According to the European Commission, the bioeconomy encompasses diverse economic activities such as agriculture, forestry, fisheries and aquaculture, bioenergy and biofuels, food and beverages, feed industry, and bio-based products and processes (Wackerbauer, 2022). As a result, and as seen in section 2.1, the implementation of the PEF, and particularly of sector-specific PEFCRs, varies significantly within bio-based sectors.

In this regard, there are some bio-based sectors in which the PEFCRs are recently developed, in development or under revision. These are (ornamental) agriculture in terms of cut flowers and potted plants; fisheries and aquaculture by means of marine fish; food and beverages such as beer, dairy products and pasta; apart from feed industry by two different PEFCRs: feed for food-producing animals and pet food. In addition, there is a newly developed PEFCR for apparel and footwear, which includes both synthetic and bio-based materials.

PEFCRs for other bio-based sectors or products are still to be developed, and these developments may face challenges, such as lack of standardized assessment methodologies, limited data availability, and varying regulatory frameworks, which can hinder progress. Moreover, some niche bio-based products may struggle to find reliable benchmarks for measuring environmental impacts, which can lead to inconsistent assessments across the bio-based landscape.

The following subsections summarise the applicability of PEFCRs for the five bio-based sectors of the CALIMERO project. This review provides information on the current state of sustainability methodology efforts within these sectors. Together with the limitations detailed in Section 3, which analyses the main methodological shortcomings in sustainability assessment, this analysis serves as a basis for further initiatives aimed at addressing these shortcomings and improving the current PEF method.

2.2.1 Construction industry

In this sector, the implementation of PEF methodologies has the potential to standardize the sustainability assessment of various construction materials. However, the construction sector is highly diverse, with multiple applications and product types. Despite the growing relevance of sustainability within the field, the application of PEF remains limited. During the EF pilot phase, PEFCRs were developed for four construction-related products: metal sheets, decorative paints, pipelines and thermal insulation.

Among the EU-funded initiatives that contribute to advancing the application of PEF in this sector, the PEF4Buildings[13] project is particularly noteworthy. Its objective was to test the applicability of the PEF methodology to office buildings and to evaluate the advantages and limitations of different approaches for defining benchmarks and performance classes for this building typology. Two case studies involving different office buildings were conducted. The focus of the project was not on obtaining final PEF results but rather on identifying methodological challenges related to the practical application of the PEF method.

In parallel, widely recognized standards have guided the application of LCA in construction, such as EN 15804

[13] https://op.europa.eu/en/publication-detail/-/publication/564726a8-b0b6-11e8-99ee-01aa75ed71a1/language-en

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and ISO 21930 at the product level, and EN 15978 at the building level.

However, despite these efforts, the sector still lacks dedicated PEFCRs specifically tailored for bio-based construction materials, which presents challenges for consistent evaluation and benchmarking. While some companies are taking the initiative to conduct LCAs using PEF principles (Buyle et al., 2013), further development of standardized guidelines will be essential for widespread adoption.

2.2.2 Textile industry

The Apparel and Footwear PEFCR[14] was officially launched following five years of work aimed at developing a standardized environmental assessment methodology for the apparel and footwear sector. The new PEFCR introduces a unified, science-based approach to product footprinting, streamlining compliance with forthcoming EU legislation such as the Green Claims Directive and Eco-design for Sustainable Products Regulation. It also fosters a common language among brands, suppliers, and auditors. Under the new rules, brands will be required to use more accurate data and adhere to stricter criteria when making environmental claims or ensuring regulatory compliance.

This PEFCR covers all categories of garments and footwear, structured into 13 product sub-categories, including T-shirts, pants and shorts, underwear, open-toed shoes, and boots, among others. Regarding its limitations —which therefore apply generally to all bio-based products— it is important to note that although the PEF method includes at least eight impact categories that affect biodiversity (i.e., climate change, aquatic freshwater eutrophication, aquatic marine eutrophication, terrestrial eutrophication, acidification, water use, land use, and freshwater ecotoxicity), there is currently no dedicated “biodiversity” impact category since an international consensus on a life cycle impact assessment method capturing that impact did not exist when the Commission’s last recommendation on the EF methods was developed in 2021.

The launch of this PEFCR represents a significant advancement for the fashion industry; however, several methodological limitations remain, particularly regarding its applicability to bio-based textiles. While leading brands are increasingly adopting PEF methodologies to improve supply chain sustainability —focusing on reducing water use, enhancing energy efficiency, and incorporating bio-based fibres— the sector continues to face challenges in assessing biodegradability, end-of-life disposal, and the environmental impact of microplastic pollution.

With respect to bio-based materials, the leather industry actively participated in the pilot phase of the PEF initiative, working with various stakeholders to develop sector-specific rules. Following this process, the PEFCR for leather was officially approved by the Environmental Footprint Steering Committee on 18 April 2018. This approval represented a significant breakthrough in providing a harmonized methodology for calculating the environmental footprint of leather produced from hides and skins of animals slaughtered for meat production, which accounts for more than 95% of leather traded globally. Notwithstanding, in terms of applicability the PEFCR for leather will continue to apply to companies that produce only leather products or whose life cycle is isolated from the textile sector. However, companies producing apparel and footwear that use leather must now use the combined PEFCR, which also addresses the environmental impacts of leather as a material[15].

[14] https://pefapparelandfootwear.eu/

[15] https://www.euroleather.com/index.php/2014-02-17-13-32-05/232-pefcr-approved

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2.2.3 Woodworking industry

As the woodworking sector increasingly adopts PEF methodologies, there is a growing emphasis on assessing the environmental impact of wood processing and product manufacturing. The introduction of PEFCRs for specific woodworking applications could provide standardized guidelines for evaluating the sustainability of various wood products, such as furniture, cabinetry, and engineered wood products (Van den Auwelant et al., 2024).

In this context, certain initiatives and projects have contributed to the advancement of PEF practices in the woodworking sector. The EFFIGE[16] project aimed to improve the environmental performances of organizations in four major supply chains: furniture, foundry, agrifood and catering services; by means of the implementation of the PEF method. In addition, different tools were developed to foment PEF adoption, such as PEFStarter[17], to fulfil market needs for evaluating and communicating their environmental impacts in a more dynamic way, although specific rules for the four above mentioned sector were not developed in the form of PEFCRs.

In parallel, the Program for the Endorsement of Forest Certification (PEFC) [18] has been proactive in aligning its standards with the EU Deforestation-free Regulation (EUDR) [19]. On November 13, 2024, PEFC's General Assembly approved the revised Sustainable Forest Management (SFM) [20] benchmark standard, PEFC ST 1003:2024. This standard includes new and amended requirements to ensure EUDR compliance for timber products sourced directly from PEFC-certified forests. PEFC has also developed an EUDR-adapted Due Diligence System (DDS) [21] module, PEFC ST 2002-1:2024, published on July 26, 2024. This module aids PEFC-certified organizations in meeting their EUDR obligations. Finally, in December 2024, PEFC hosted a webinar[22] detailing these updates, emphasizing their commitment to supporting stakeholders in achieving EUDR compliance. Consequently, these developments reflect a concerted effort within the forestry sector to enhance environmental sustainability and adhere to evolving regulatory standards.

However, challenges remain in terms of data availability and establishing consistent metrics for assessing the environmental impact of different wood species and sourcing practices. Overall, while the construction and woodworking industries are making progress in implementing PEF and PEFCRs, further efforts are needed to establish comprehensive frameworks that can facilitate standardized assessments and drive sustainability across these bio-based sectors.

2.2.4 Pulp & paper industry

During the EU Environmental Footprint pilot phase, a PEFCR for Intermediate Paper Products was developed. Intermediate paper products are those that require further conversion for their final application. In these circumstances, an intermediate material may fulfil a number of different functions depending on the performance

[16] https://www.lifemagis.eu/index.php/team-member/life-effige-en

[17] https://pefstarter.enea.it/

[18] https://pefc.org/

[19] https://environment.ec.europa.eu/topics/forests/deforestation/regulation-deforestation-free-products_en

[20] https://www.pefc.org/what-we-do/our-approach/what-is-sustainable-forest-management

[21] https://environment.ec.europa.eu/news/eu-deforestation-regulation-information-system-launches-2024-12-06_en#:~:text=The%20Information%20System%20is%20a%20key%20tool%20that,available%20for%20submitting%20and%20managing%20due%20diligence%20statements.

[22] https://www.pefc.org/events-training/pefc-on-the-path-to-eudr-alignment-december-2024

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required of the final product.

Currently, there is no officially endorsed PEFCR for final consumer paper products. However, many European paper manufacturers already implement LCA-based standards that are compatible with the PEF methodology. The sector has made significant efforts to reduce its environmental footprint by increasing recycled content, improving energy efficiency, and integrating PEF-based assessments into corporate sustainability strategies to align with EU environmental criteria.

In practice, companies such as Tetra Pak[23] apply PEF principles to compare virgin vs. recycled paperboard, thereby supporting the development of low-impact packaging solutions.

Regarding EU-funded initiatives, the LIFE CO2PES&PEF[24] project is particularly relevant. It applies the PEF methodology to forest-based products and aims to develop a toolkit to help forestry and wood-based enterprises replicate PEF assessments in other sectors. The project also seeks to create a draft PEFCR, which will be tested across three pilot companies to evaluate its representativeness for the sector and determine whether further refinements are required.

2.2.5 Biochemical industry

The industry is adopting PEF methodologies to assess the sustainability of bio-based chemicals, but challenges remain in comparing them to fossil-based counterparts. The lack of dedicated PEFCRs for bio-based chemicals makes standardized assessments difficult, although ongoing research is improving LCA models. For instance, companies like Novamont[25] and NatureWorks use PEF methodologies to measure the environmental footprint of biodegradable plastics[26], such as PLA (polylactic acid). Additionally, companies like Nestle[27] conduct PEF-aligned LCAs to compare biofuels with conventional fossil fuels, demonstrating significant CO_2 emissions reductions.

Currently, there is no PEFCR targeting either the biochemical or the chemical industry as a whole, but specific PEFCRs have been developed for certain products such as liquid laundry detergent, decorative inks and shampoo.

3 MAIN METHODOLOGICAL GAPS IN SUSTAINABILITY ASSESSMENT OF BIO-BASED SECTORS

In the CALIMERO project, a series of methodological gaps were identified (D1.3), and based on these findings, methodological developments for the LCSA of bio-based sectors were proposed under WP3.In this regard, a summary of methodological gaps related to key areas of concern within the bio-based sectors, focusing on the limitations found in the PEF methodology, is presented below. These can be distinguished between environmental gaps within the PEF framework and aspects that go beyond PEF, such as social or local risk-related dimensions.

Environmental gaps

- **Biodiversity & Ecosystem Services**

[23] https://www.tetrapak.com/sustainability/focus-areas/biodiversity-and-nature/responsible-sourcing

[24] https://lifeco2pefandpes.eu/en/

[25] https://packagingspeaksgreen.com/en/materials/novamonts-project-calculate-carbon-footprint-mater-bi

[26] https://www.natureworksllc.com/sustainability/eco-profile-and-life-cycle-analyses

[27] https://www.nestle.com/sites/default/files/asset-library/documents/library/documents/corporate_social_responsibility/2011-csv_environmental-sustainability.pdf

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The PEF methodology currently faces several challenges in providing a comprehensive assessment of bio-based products, particularly with regard to impacts on ecosystem services and biodiversity, as these are not covered by its recommended toolbox. This limitation means that non-climate impact categories cannot be effectively quantified or modelled, which hinders the assessment of offsets and could result in burdens being transferred between these categories.

In terms of biodiversity impacts, the PEF Rules Guidance v6.3 allows for the inclusion of related information, but only as optional supplementary data, rather than as a core component of the assessment framework.

With regard to ecosystem services, the land use impact is quantified with the indicator of soil quality index (SQI) based on LANCA® (Land Use Indicator Value Calculation in Life Cycle Assessment). It is important to note that the current LANCA® Characterization Factors (CFs) only account for the permanent transformation impacts and the reference situation corresponds to the quality (for each indicator) of the potential natural vegetation of the biome with the largest area share (i.e., the main biome) of a country. Consequently, the LANCA® model, recommended in PEF, lacks CFs for air purification and focuses on soil-related services instead.

- **Toxicity**

The conversion of chemical emissions into potential ecotoxicological impacts can be achieved using substance-specific CFs. These factors should be based on scientifically validated, peer-reviewed environmental models operating within the constraints of LCA boundaries. In this context, the USEtox model is the internationally recognised framework for characterising ecotoxicological human and environmental impacts.

Including toxicity-related impacts in the PEF methodology has prompted the European Commission's Joint Research Centre (EC-JRC) to prioritise improving existing models. To develop a more robust and transparent approach to CF calculation, the EC-JRC has proposed the following methodological advances: implementing a selection process to identify highly reliable data, adopting a more conservative alignment of freshwater toxicity data with that used in chemical risk assessment, and introducing a robustness factor (RF) to account for uncertainties associated with multimedia modelling of various substance classes, including metals and inorganic compounds.

This refined framework enables CFs to be generated for around 6,000 substances, greatly expanding the range of chemicals included in life cycle inventories for freshwater ecotoxicity. However, significant gaps remain, particularly with regard to the inclusion of additional environmental compartments, the integration of broader chemical groups and consistent application of hazard concentration (HC) metrics for metals and organic substances (Sala et al., 2022).

- **Carbon accounting**

Within the PEF methodology, the carbon footprint is accounted for using the Global Warming Potential (GWP) over a 100-year time horizon, without applying any temporal differentiation. The most recent EF 3.1 impact assessment method assigns a value of zero to both the sequestration and emissions of biogenic carbon flows. This "0/0" approach effectively neutralises the climate change impact of biogenic CO_2, while still recording the flows. However, ongoing discussions suggest a potential shift towards adopting a '-1/1' accounting method, in which carbon sequestration would be represented by a negative value and emissions by a positive one. This approach would preserve the climate relevance of biogenic carbon flows while retaining the 'biogenic' label to distinguish them from fossil-based carbon.

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Another methodological issue arises from how time horizons are handled in LCIs, particularly in certain PEFCR and cases (e.g. landfilling datasets) where emissions are only considered until a time horizon of 100 years. While this aligns with the GWP100 indicator, it introduces a temporal cut-off that may be inconsistent with the broader life cycle of the product system, since the actual duration of processes beyond this timeframe is not considered.

Finally, the modelling end-of-life stages, which is currently addressed through the Circular Footprint Formula (CFF), is also a critical methodological feature of PEF. This influences the overall carbon balance and the allocation of environmental impacts between product life cycles, adding complexity to the interpretation of carbon-related results.

➲ Modelling of Cascade/Circular economy

The evaluation of cascade effects within a circular economy framework still lacks a clear and consistent definition. In the PEF Guide, circularity is addressed through the CFF. The CFF is an allocation method that determines the share of impacts associated with end-of-life processes such as collection, sorting, recycling, and recovery, as well as the avoided impacts resulting from the substitution of primary raw materials or energy. These impacts are distributed between the life cycle in which the recycled material becomes available and the life cycle in which it is used.

Schrijvers et al. (2021) identify several issues with the CFF, including errors in the formula by merging the collection rate and the recycling efficiency rate. They also argue that it mixes attributional and consequential modelling approaches. This combination may lead to inconsistencies when the CFF is applied outside the specific context of the PEF framework. Additionally, the authors analyse the quality ratio parameter included in the CFF, which is intended to reflect the quality of incoming or outgoing secondary materials in comparison with the quality of the substituted primary materials at the point of substitution. This quality parameter is based on a price ratio, which may not always provide an accurate reflection of the relative quality of materials. As a result, it may be unreliable for assessing downstream effects related to the degradation in quality of bio-based materials that are recycled multiple times.

Other limitations of the modelling of circular processes in the PEF Guide that were brought up in **D3.3** of WP3 are the following:

- No parameter is included in the CFF for *using* recovered energy, resulting in potential modelling inconsistencies between supplying and using recovered energy
- Mandatory modelling of primary raw material use due to restricted options for parameter A, even if this is not corresponding with reality
- Additional guidance is needed to identify the (substituted) primary raw material source
- Additional guidance is needed to identify the (substituted) energy production source
- Only substitution of primary materials is modelled, downstream effects of this substitution (e.g. differences in transport, use, or EoL) are not considered. This especially results in strange results for the user of a recycled material, that needs to model primary production, without modelling the consequences of using a primary material (see for example the leaching of borax in the biochar scenario in **D3.3**).
- Final disposal of waste after multiple reuse cycles needs to be modelled, although the relevant processes may be unknown.
- A material that can be recycled multiple times in a cascading system will be assessed the same as a

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material that is only recycled once.

- Only materials that are recycled in a closed loop will benefit from multiple reuse cycles.

Gaps beyond PEF

➲ Occupational Safety and Health

The PEF methodology considers the human toxicity impacts of environmental exposure to hazardous substances. However, it does not explicitly address occupational exposure, workplace-related toxicity or the health effects of working. Consequently, the direct impacts on workers are currently beyond the scope of the PEF framework. This limitation reflects the fundamental scope of environmental LCA methodologies, which focus on elementary flows across the environment-technosphere boundary, rather than strictly local consequences. Impacts on workers are typically managed through dedicated risk assessments, environmental or social impact studies, and regulatory frameworks such as REACH.

In the context of LCIA, human toxicity is linked to the burden of disease and is based on principles of exposure assessment and toxicological response, particularly the dose–response relationship. However, such mechanistic toxicity data generated using in vivo, in vitro and in silico models, are designed for risk and safety assessment, often in a regulatory context, which is challenging to incorporate into the LCA framework, because LCA requires aggregate, product- or process-level impact indicators, whereas occupational exposures are highly site-specific, variable, and context-dependent, making it difficult to translate detailed toxicological data into standardized LCA metrics.

Currently, USEtox is the globally accepted consensus model for calculating human toxicity CFs within LCIA. The Human Toxicity Task Force's efforts, as reported in the GLAM Phase 2 initiative (Rosenbaum et al., 2008), have highlighted several areas in need of further development. These include the consideration of chemical exposure in occupational environments and the incorporation of 'near-field' human exposure pathways, such as direct dermal contact with material surfaces.

➲ Social LCA Indicators – job potential

The PEF focuses on the estimation of environmental impacts through the LCA methodology, so S-LCA is not included in its framework. However, the European Commission has recognized the growing importance of including both economic and social impacts in order to carry out more sustainability assessments. To this end, the EC-JRC actively supports and contributes to the further development of S-LCA within the PEF methodology by publishing reports and guidelines on this methodology. These include the report *Social Life Cycle Assessment*, which reviews the state of the art and challenges in supporting product policy (Sala et al., 2015); a technical report on assessing social impacts in the supply chains of raw materials and semi-finished products (Mancini et al., 2018); and a scientific paper applying S-LCA to food production and consumption to capture social sustainability aspects (Mancini et al., 2023). Nevertheless, none of these works directly addresses or explicitly mentions the concept of the bioeconomy.

➲ Criticality evaluation

The transition to a low-carbon economy has increased dependence on critical raw materials, especially metals and some bio-based resources, prompting the development of criticality assessment methodologies to evaluate supply risks and vulnerabilities. The PEF methodology only accounts for resource depletion (minerals, metals, and

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fossil fuels) and does not take into account potential challenges related to the current accessibility of resources for ongoing economic activities, nor the quality degradation or the accessibility-related dissipation related to the life cycle of resources. A revision of the current use of the abiotic depletion indicator to a focus on dissipation is recommended.

The PEF Guide does not consider other aspects associated with resource criticality, such as price fluctuations, supply security, or reputational risks. However, it is not recommended to add criticality indicators as part of the PEF Guide, whose environmental results are targeted to consumers. Criticality assessments focus on a "system at risk", which can be the producing company or a local economy. Consumer choices or not logically informed by criticality results.

Nevertheless, companies who conduct PEF studies for their products could benefit from a tandem assessment of their criticality, even though the criticality results are not communicated to the same audience as the environmental impacts. The results of the criticality assessment can subsequently be used for the internal monitoring of the resilience of the company's production processes.

4 Guidelines and recommendations to develop PEF and PEFCRs for LCSA practitioners

After examining the applicability of the PEFCRs within the bioeconomy context, particularly for the five bio-based sectors involved in the CALIMERO project (Section 2.2), and identifying methodological gaps (Section 3) within the PEF methodology, it is now appropriate to propose tailored guidelines aimed at improving the environmental evaluation process standard.

To this end, **Table 1** presents recommendations, including both short-term and long-term actions, to be considered for inclusion in future iterations of the PEF method.

Table 1. Overview of CALIMERO's contribution to key methodological gaps and recommendations for implementation in future updates of the PEF method.

Key aspect	Contribution from CALIMERO	Recommendations
	Environmental aspects	
Biodiversity & Ecosystem Services	CFs were developed to assess the impact of land use on biodiversity in relation to habitat connectivity (loss), as well as the impact of land use on the removal of particulate matter. Currently, these are only available for Sweden, but there is a procedure for further expansion and application.	Long term: – Create a consensus process for biodiversity CFs. – Integration of CFs of CALIMERO for land-use related effect on biodiversity through land connectivity and particulate matter removal, covering two new impact pathways.

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Toxicity	CFs for new substances were developed, based on USEtox, (the "scientific consensus" approach) and ProScale (the "industry consensus" approach), for human health impacts as well as ecotoxicity, both by applying computational prediction approaches and/or machine learning.	<u>Short term</u>: - Implement new substance CF that are already aligned with PEF. <u>Long term</u>: - Apply USEtox and another method (e.g. ProScale) in parallel as sensitivity analysis. - Thoroughly review and potentially revise the toxicity approach to better align with REACH, possibly renaming it (e.g. EFtox) to reflect "deviation" from the original USEtox.
Carbon accounting	To allow for a full dynamic life cycle inventory (e.g. spreading greenhouse gas emissions over time across a product system) a temporal database (DyPLCA) was updated, containing temporal parameters, for all ecoinvent 3.10 processes (~25000). This can then be run using the dedicated DyPLCA computational framework.	<u>Short-term</u>: - All carbon accounted equally (-1/+1) with end-of life considerations. - Use two complementary midpoint indicators for climate change, to differentiate short-term and long- term impacts. <u>Long-term</u>: - Push for data providers to provide biogenic and fossil carbon flows in life cycle inventories. - Use the recommendations in the ILCD handbook for classification of elementary flows to enable a more flexible and accurate dynamic assessment of GWP. The ILCD Handbook classifies elementary flows by how long carbon stays out of the atmosphere: short-term (returns within ~100 years), long- term (stored over 100 years), and permanent (sequestered indefinitely). This classification helps decision makers track and assess the timing of carbon impacts at a macro level. - Integrate a dynamic carbon footprint and dynamic LCA, with consistent temporal consideration across LCI & LCIA, with temporal data for both foreground and background system. For the latter, in PEF, the PEF LCI- database, should add such temporal information. - Add temporal information to LCI dataset to allow for modelling of greenhouse gas flows over time across the life cycle.

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Cascading modelling	Findings indicate that PEF methodology may be improved for a more consistent modeling of cascades/circularity. PEF could better account for cascading by reflecting quality loss and functional equivalence across multiple cycles. This would improve accuracy in modeling long-term circularity.	Short-term: - Correct the erroneous calculation of collection rates and recycling efficiencies. - Include a term in the CFF for downstream effects of using a recycled material instead of primary material, such as changes in emissions or transport (e.g. due to weight differences). Long term: The use or development of circularity indicators to complement PEF studies (as recommended in D3.3) may be considered to overcome limitations of current disregarding of multiple cascades.
Circularity Modelling: Energy Recovery	Findings suggest that PEF needs to enable the inclusion of recovered energy streams with low economic value or limited market demand.	Short-term: PEF provides guidance on and enables the use of the B factor for accounting for energy recovery. This term needs to be added also at the energy consuming side. Additionally, more explicit guidance to identify the substituted production processes of heat and electricity is required. The same is valid for the avoided primary production processes of materials, although this may be specified in PEFCRs.
Beyond PEF		
Occupational health and safety	An indicator related to exposure limits, known as the Occupational Exposure Limit (OEL) Indicator, has been developed along with its three levels of assessment. This additional indicator is designed to address occupational exposure limits for chemicals and to support the management of those substances accordingly.	Short term: - The OEL indicator can be used as an additional information in health and safety Reference Scale approaches where indicators like "presence of a formal policy concerning health and safety" and "appropriate work equipment and training" are used or it can be used as a stand-alone indicator where needed.
Social LCA - Job Creation Potential	Development of a Job Creation Potential (JCP) indicator which quantifies the total number of jobs that a product system can generate through the supply chain. In this sense, it represents the aggregation of jobs created in the foreground system and those created by the background system. Jobs created in foreground systems refer to those required for the operation of a company (i.e., employees directly hired), while jobs created in background systems are those generated by suppliers to support the project	Long-term: - To establish a consensus between (bio)economy strategies and S-LCA methodologies. - Integrate the JCP indicator into LCSA methodologies.

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Criticality evaluation	Development of a criticality assessment framework. While other methods have focussed on comprehensiveness of sustainability assessment and/or the provision of a single result, in CALIMERO, it was argued for a step-wise procedure that explicitly identifies an economic stakeholder of interest, allowing for the identification of sources of potential economic instability and mitigation measures	Long term: - Consider using the criticality assessment developed by CALIMERO as a way to consider criticality aspects, for the *internal* assessment of company's production processes, in parallel of conducting PEF studies.
Other issues - Decision support	CALIMERO has developed and validated simulation models for various bio-based industrial processes (woodworking, textile, construction, pulp and paper, and biochemical sectors) using recommended solutions derived from the CALIMERO Multi-Objective Optimization (MOO) framework. Comprehensive uncertainty and sensitivity analyses were performed for each case study to ensure transparent and reliable decision-making.	Short term - Facilitate coupling with MOO through making datasets readily available in dedicated software tools

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4.1 Sector-specific recommendations

Not all of these recommendations can be applied uniformly across all bio-based sectors. For this reason, prioritization is required based on each sector's relevance and the feasibility of implementation. This section highlights which general PEF recommendations should be prioritized for the specific CALIMERO sectors and considered for inclusion in their related PEFCRs, based on the outputs of **D5.4**. It is important to note that in this Deliverable, only the textile, woodworking, and construction sectors were analysed. Therefore, while prioritization is provided exclusively for these sectors, this report also suggests relevant general recommendations.

In **D5.4**, a Multi-Criteria Analysis (MCA) was conducted to evaluate indicators using criteria defined in collaboration with project partners. These criteria are organized into two main categories: **Incentives**, which measure how much an indicator can help inform strategic decisions, motivate action and reveal opportunities or risks; and **Quality**, which evaluates the ease and reliability of obtaining the necessary data, including its accuracy, availability, timeliness and accessibility.

Indicators with high incentives and high quality are considered high priority because they combine reliable, accessible data with a strong potential to guide strategic decisions. Conversely, indicators with low quality and low incentives are considered the least useful and are recommended for postponement or exclusion. Indicators with high quality but low incentives are suitable mainly for reporting and consultation, while those with low quality but high incentives reveal critical data and methodological gaps and should be prioritized for future refinement and investment. The CALIMERO indicators with high incentives are analysed below.

For the textile sector, the indicators with high incentives and high quality include circularity metrics such as the circular material rate and the end-of-life recycling rate, demonstrating that core circular economy principles are considered actionable. Toxicity-related indicators are also part of this group. These represent a solid starting point for developing a textile-specific sustainability framework and should be prioritized for adoption. Conversely, indicators with low quality but high incentives are largely dominated by social indicators and advanced circularity metrics, such as the reuse rate in closed loops and the percentage of water demand from circular sources. These are highly desirable but not yet readily measurable due to current data limitations.

In the woodworking sector, the ideal indicators —those with high incentives and high quality— are primarily climate-related metrics, especially those measuring long-term, biogenic, and fossil emissions. These reflect the sector's significant reliance on biomass and forestry resources, making such indicators highly actionable and relevant. Criticality and toxicity indicators are also considered important within this sector. Indicators with low quality but high incentives include social indicators, complex circularity metrics, and occupational health and safety measures, all of which require further methodological development and improved data availability.

For the construction sector, priority indicators include a wide range of metrics, such as optimization indicators, criticality metrics, and, similar to woodworking, those measuring long-term, biogenic, and fossil emissions. Among the low quality but high incentives group, several indicators relate to circularity challenges, which remain strategically relevant but difficult to implement due to current data gaps.

To sum up, despite their relevance, many CALIMERO indicators fall into the low quality but high incentives category. These are strategically important but currently limited by data availability or immature methodologies. While they address key sustainability concerns, they are not yet ready for full implementation and require further refinement. Indicators such as circularity, criticality, dynamic carbon footprint, job creation, and novel toxicity factors represent emerging tools with high potential impact. To unlock this potential, targeted efforts in data collection, methodological development, and sector-specific adaptation are essential to ensure their effective integration into future PEFCRs.

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5 Main conclusions

In summary, this report emphasizes the necessity of adapting and improving PEFCRs to effectively address the challenges posed by the bioeconomy. Through the CALIMERO project, the focus has been placed on five key sectors, each of which has been reviewed for its current implementation status of PEFCRs.

Based on the main outcomes obtained, it can be stated that although PEFCRs provide a structured, standardized framework for environmental assessment, their applicability is limited to certain industries, including construction, woodworking, textiles, pulp and paper, and biochemicals when addressing certain aspects (e.g., biodiversity, dynamic carbon footprint, toxicity, etc.).

Consequently, recommendations have been proposed to address these methodological limitations and continue paving the way for sustainable development and PEFCR advancements. However, these proposals should be validated through their applications into real case studies, apart from across additional sectors. In this way, it will be possible to allow a gradually integration into future PEFCRs revisions developed by LCSA experts.

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