# D2.3 Review and Meta-analysis of Environmental and Circular Performances of Industrial Biobased Systems

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BBPs: Biobased Products
IBBS: Industrial Biobased System
LCA: Life Cycle Assessment
TRL: Technology Readiness Level
EOU: End of Use
EoL: End of Life
WP: Work Package

# Abstract

The excessive dependence on fossil resources has led to substantial climate challenges and increasing resource constraints. This situation underscores the importance of industrial biobased systems as a vital alternative to traditional fossil-based products. However, sustainability and circularity assessment are critical factors in determining the viability of this transition. This report comprehensively reviews industrial biobased systems' environmental and circular performance, concentrating on three primary sectors: bioplastics, biochemicals, and wood-based products. Through an analysis of various review and meta-analysis studies, the findings reveal significant benefits, including reduced greenhouse gas emissions, non-renewable energy uses, and the potential for enhanced circular resource flows. Nonetheless, trade-offs often accompany these advantages, such as increased eutrophication, acidification, and variable land-use impacts.

To provide a structured framework for analysis, an environmental performance matrix has been developed to highlight both environmental benefits and potential trade-offs in each sector. Across all three sectors, methodological inconsistencies related to biogenic carbon accounting, system boundaries, functional units, and end-of-life pathways contribute to significant uncertainty in interpreting results and formulating precise conclusions. Despite these uncertainties, well-designed life cycle assessments and emerging practices within the circular economy, such as cascading use, recycling, and industrial composting, present promising strategies for improving the sustainability profile of biobased value chains. This report emphasises the necessity of adopting a life cycle perspective and employing harmonised assessment frameworks to evaluate biobased systems, giving recommendations. By leveraging technological innovations, utilising sustainable feedstock, implementing effective end-of-life management strategies, and adhering to standardised methodologies, pathways can be established toward a more sustainable and circular biobased products bioeconomy.

# 1 Introduction

## 1.1 Background and Objectives of the Project ESCIB

Across the globe, organisations and countries are implementing policies to reduce the environmental impacts of fossil-based products and promote a sustainable transition to innovative, eco-friendly alternatives. This shift has led to more innovative products derived from biological sources, which can replace fossil-based materials. However, conducting life cycle and circularity assessments is essential to determine whether such products are more environmentally friendly and utilise resources more effectively. The findings from these assessments will allow us to evaluate the environmental impacts of products currently in development or already available in the market at varying technological readiness levels (TRL). Additionally, such assessments will provide valuable guidelines for crafting policies supporting sustainable development and using alternative biobased products (BBPs).

The ESCIB project aims to enhance the sustainability of the biobased economy in Europe by developing standardised assessment methodologies for evaluating the sustainability of BBPs. Its primary goal is to create a robust framework that assesses the sustainability of BBPs across various TRLs. This methodology will adopt a holistic life cycle assessment (LCA) approach to evaluate the environmental impacts and circularity within biobased value chains. Additionally, it will address potential socio-economic trade-offs and align with the European Green Deal (EGD) and the Circular Economy Action Plan (CEAP) objectives.

The ESCIB project includes industrial partners who make BBPs at varying TRLs to ensure that the sustainability methods we develop can be applied effectively. Certification organisations can then use these methods to label and certify BBPs. Ultimately, our results will guide research and innovation programs in the biobased sector.

## 1.2 Terms and Definitions in this Report

This report defines the terms and definitions used in Khan et al. (2024b), while the sectors analysed in this study are classified in Khan et al. (2024a).

## 1.3 Objectives of this Report

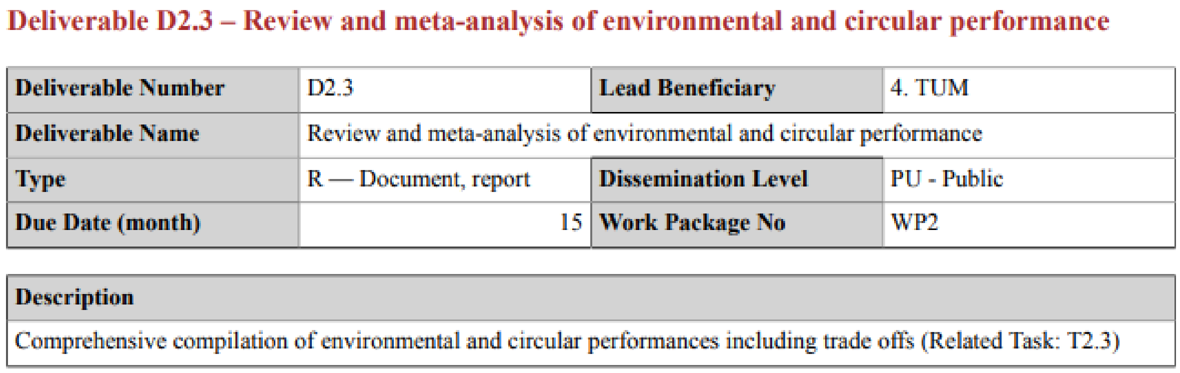
Work package (WP)2 of the ESCIB project focuses on identifying the EU's best practice industrial biobased systems (IBBS). Therefore, the WP2 works on several tasks, including sustainability and circularity assessment of key IBBS in the EU. The objectives of this report are the following,

- To provide an umbrella review of published review and metanalysis studies that examine the environmental and circular performance of IBBS, covering bioplastics, biochemicals and wood-based products.
- To determine the main environmental hotspots in those IBBS.
- Present a unified overview of environmental trade-offs and benefits for each sector using a visually structured matrix.
- Identifying the key uncertainty factors and methodological challenges and presenting recommendations.

## 1.4 Deliverable D2.3 of WP2

This report presents the deliverable D2.3 of WP2 as shown in Table 1-1.

*Table 1-1: Deliverable D2.3 of the ESCIB project.*



**Deliverable D2.3 – Review and meta-analysis of environmental and circular performance**

| | | | |
|---|---|---|---|
| **Deliverable Number** | D2.3 | **Lead Beneficiary** | 4. TUM |
| **Deliverable Name** | Review and meta-analysis of environmental and circular performance | | |
| **Type** | R — Document, report | **Dissemination Level** | PU - Public |
| **Due Date (month)** | 15 | **Work Package No** | WP2 |

| **Description** |
|---|
| Comprehensive compilation of environmental and circular performances including trade offs (Related Task: T2.3) |

# 2 Materials and Methodology

An umbrella literature review was conducted to synthesize existing reviews and meta-studies on environmental and circularity assessments of BBPs. This study analysed three sectors: bioplastics, biochemicals and wood-based products. For this purpose only review studies, meta-analysis and grey literature (e.g., EU reports) that provide comprehensive evaluations on the sustainability and circularity assessment were included. The literature search was performed initially at Level 1 using two databases i.e., Google Scholar and Web of Science, with key words related to sustainability assessments as shown in Figure 2-1.

The screening process involved evaluating titles, abstracts, and, where necessary, the results sections to determine eligibility. After screening, it was observed that literature on sustainability and circularity assessments for wood-based products was limited. Consequently, a Level 2 search was conducted to specifically retrieve review papers on wood-based products (Figure 2-1). Grey literature i.e., EU reports and other supportive literature are also included for the evaluation. Main literature that is used extensively are reported in Table 4-1.

First of all methodological considerations are evaluated focusing on accessing the important aspects in sustainability assessments including the impact categories evaluated for BBPs as presented in section 3.1. A comprehensive overview of the environmental sustainability assessment of BBPs compared to fossil-based products was developed. The positive environmental benefits and associated trade-offs were analyzed for each BBPs sector. In addition, circularity assessments were conducted, focusing on end-of-life (EoL) strategies and its significance in circular bioeconomy. A hotspot analysis was performed, and uncertainty factors were discussed to explain variations in impacts. An environmental sustainability assessment matrix was constructed to summarize environmental benefits and trade-offs across all reviewed studies and meta-analyses (Table 3-3, Table 3-4 and Table 3-5). This matrix was developed by evaluating the overall environmental performance of BBPs against fossil-based products in each sector. In the matrix, BBPs are categorized as having lower or higher impacts based on the general trend observed in the literature or the prevalence of products showing lower or higher impacts. For example, when the majority of BBPs in a review or meta-study exhibit lower global warming potential (GWP) compared to fossil-based products, this is classified as “lower” in the matrix represented by green box. Conversely, if most BBPs show higher impacts for a specific impact category, it is classified as “higher” represented by red colour box. Where information is unclear or not explicitly reported, the corresponding cell in the matrix is represented as grey box.

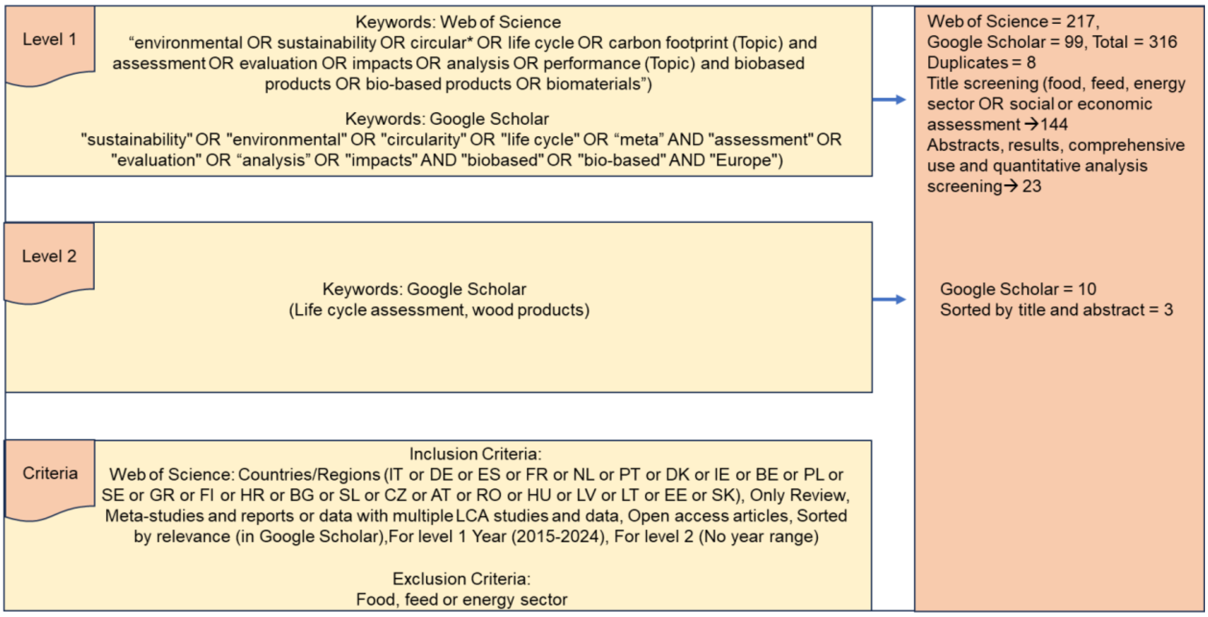


*Figure 2-1: Methodology used in this study for collection of literature for conducting an umbrella review of sustainability and circularity assessment of BBPs.*

# 3 Results and Discussion

This section presents the findings from prior reviews and meta-studies that evaluate the environmental and circularity dimensions of IBBS. It classifies how these products are assessed LCA and related methodologies, highlighting the environmental advantages and potential trade-offs, including risks of eutrophication and increased land use. In doing so, it identifies crucial factors that influence the overall sustainability profile of biobased systems, such as feedstock selection, conversion technologies, and end-of-life scenarios. The subsequent subsections provide a deeper analysis of methodological trends and challenges, focusing on environmental and circularity assessments, including potential hotspots. Key factors leading to uncertainty are identified, and recommendations are reported to enhance the sustainability and circularity assessments of BBPs, including methods for conducting accurate evaluations that support informed decision-making.

## 3.1 Methodological Trends and Challenges in Analysing IBBS Sustainability Assessment

LCA is used to assess the environmental impacts of biobased-based products. LCA methodology is essential for comparability and correct evaluation of biobased product systems. A review by Gaffey et al. (2024) determines key methodological considerations while conducting LCA for BBPs to have more transparency in biorefinery LCA, which is also valid for all bio- and wood-based product systems (Figure 3-1).

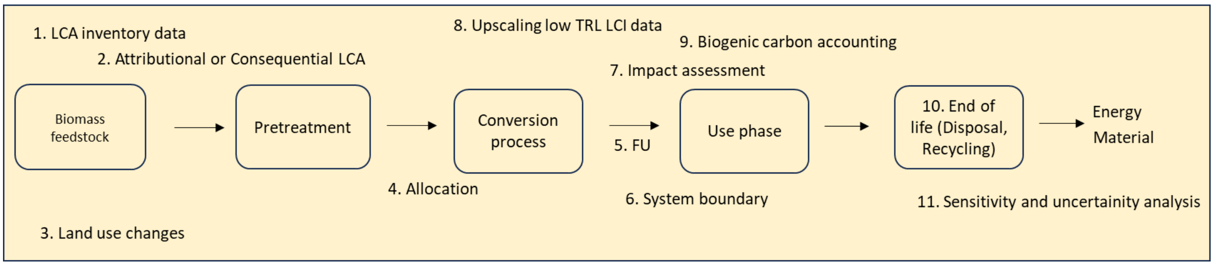


*Figure 3-1: Key methodological considerations when applying LCA to bio- and wood-based systems and associated supply chains (adapted from [(Gaffey et al. 2024)](#)).*

BBPs can have positive environmental impacts but may also present trade-offs in specific categories. This makes environmental impact assessment challenging in determining which impact categories should be considered when assessing the overall sustainability of BBPs. Therefore, it is important to understand the impact categories most used in LCA studies and identify which ones are crucial for making informed decisions or statements regarding the sustainability assessment of BBPs.

In this aspect, a Swedish open space workshop group (Martin et al. 2018) composed of participants from researchers and industrial practitioners carried out extensive discussions and voting to determine important environmental sustainability impact categories for assessing BBPs. Voting by these experts leads to determining the most important environmental impact category as climate change, followed by biodiversity and water use (Figure 3-2).

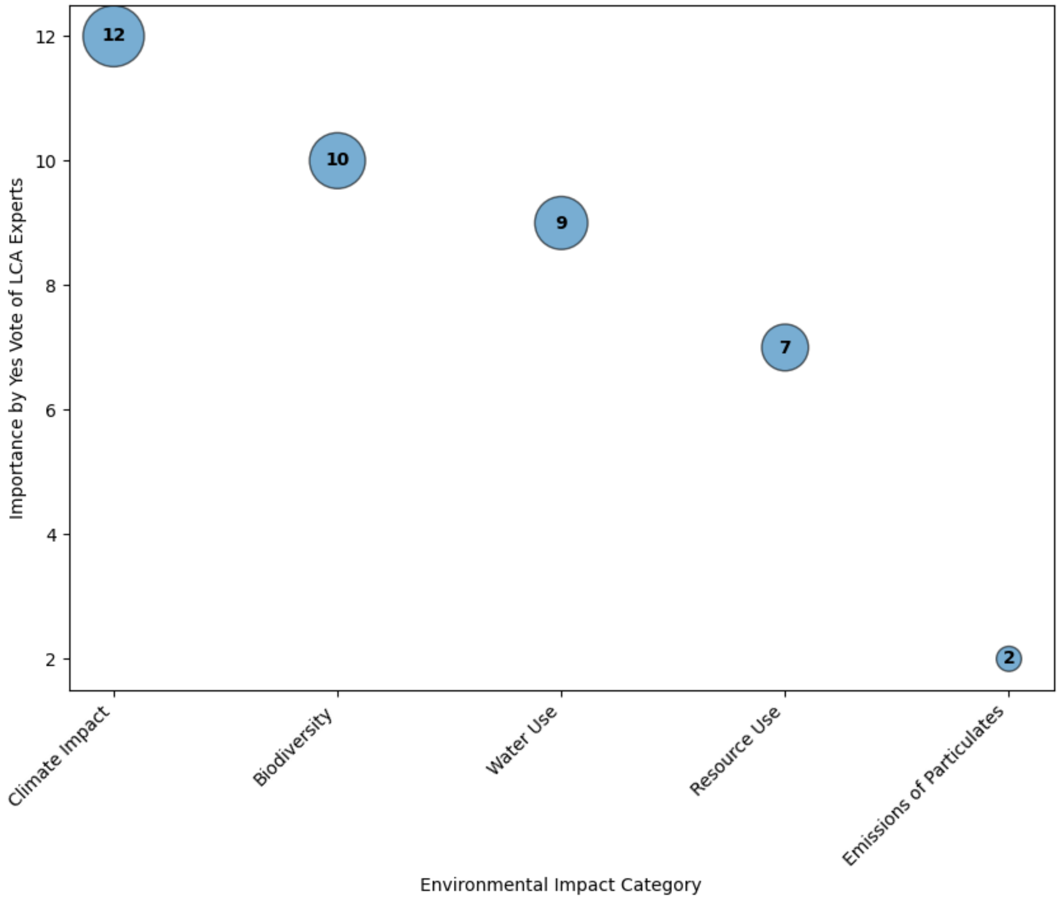


*Figure 3-2: Environmental sustainability impact categories were identified by the Swedish open space workshop and selected for discussions as necessary by yes votes from LCA experts in the sustainability assessment of biobased products (data source (Martin et al. 2018)).*

Furthermore, Martin et al. (2018) analysed LCA studies impact categories with planetary boundaries framework (PB) (Steffen et al. 2015) and EU guide to product environmental footprints (PEF) (EC 2013) and found that climate change is the most explicit impact category that is mentioned in all studies and also explicitly mentioned in other frameworks. However, acidification and eutrophication, which are discussed in most of the LCA studies, were not seen as important by the PB and workshop experts. Biodiversity which is not reported by any reviewed LCA studies was found to be explicit by PB, workshop experts and PEF as explicit impact category. Similarly, review studies by van Schoubroeck et al. (2018) and Ögmundarson et al. (2020a) found that most LCA studies regarding biochemicals analysed GWP, cumulative energy demand, freshwater eutrophication, and acidification in their sustainability assessment of biobased chemicals. Furthermore, review studies by Deviatkin et al. (2019), Costa et al. (2024) and Werner and Richter (2007) also report that climate change impact is mainly analysed in the impact category for wood-based products.

## 3.2 Environmental and Circularity Assessment of Biobased Plastics

### 3.2.1 Overview of Bioplastics

The harmful environmental impacts of fossil-based plastics have stimulated research and development to demonstrate bioplastics as a viable alternative. Ali et al. (2023) reported from the works of (Chinthapalli et al. 2019; Chong et al. 2021; Roy Chong et al. 2022) that bioplastics derived from biomass resources such as starch, corn, sugarcane, and lignocellulosic components cannot only enable the transition to a circular economy but also can reduce the extraction of fossils resources, carbon footprints and further environmental impacts that arise at the end-of-life (EoL).

Most plastics are not biodegradable, and their complete disintegration can release micro- and nanoplastics in the natural environment that negatively impact aquatic ecosystems and human health (Ali et al. 2021; R. Geyer et al. 2017; Al-Tohamy et al. 2023a; Al-Tohamy et al. 2023b; Al-Tohamy et al. 2022). This is also valid for bioplastics, which can be biodegradable or not. However, due to their renewable resource basis, biomass, "bio-based polymers" or "bioplastics" have been proposed as a potential solution for mitigating the detrimental impacts of petrochemical plastics on the environment and human health (Ali et al. 2023). Furthermore, most fossil-based plastics can be replaced by a wide variety of bioplastics, i.e., LDPE can be substituted by bio-PE, PHA, PLA and TPS (Table 3-1). However, extensive and well-designed LCA studies are necessary to correctly provide scientifically based evidence on the environmental sustainability of bioplastics and how they benchmark compared to fossil-based plastics (Ali et al. 2023).

Bioplastics are classified into biodegradable and non-biodegradable. Biodegradable bioplastics are PLA, PHA, PBS, PBS, PBAT, CR, CP and TPS or SCPC (starch-containing polymer compounds). They have a production capacity share of almost 56.3 % worldwide in 2024 and 72% in EU+3 in 2023, and the non-biodegradable bioplastics are bio-PE, bio-PET, PA, and PTT. They have a share of 43.7% worldwide in 2024 and almost 26% in EU+3 in 2023) (Ali et al. 2023; Plastics Europe 2024; Ishimwe 2024b). Among biodegradable plastics production in EU+3, PLA share is 25%, PBAT 17%, casein polymers 17% and starch-containing polymer compounds stand at 9% in 2023 (Plastics Europe 2024). Sector-wise, global production of bioplastics shows that packaging has the highest share of around 45%, fibres (woven and non-woven) has almost 20%, and consumer goods at 14%, respectively (Ishimwe 2024a).

Biobased plastics can be manufactured from first, second and third-generation feedstocks; however, currently, most bioplastics are derived from carbohydrate-rich first-generation feedstocks, such as corn, sugar, cane, castor oil plant, potato or wheat. They are most suitable for bioplastics manufacturing that has reached the commercialisation level (Brizga et al. 2020; Gerassimidou et al. 2021; European Bioplastics e.V. 2024a; Ögmundarson et al. 2020b; Spierling et al. 2018a; Spierling et al. 2018b).

*Table 3-1: Substitution potential of bioplastics that can replace fossil-based plastics. Bioplastics substitutes are the plastics analysed in LCA studies compared to respective fossil-based polymers or as technical substitutions of bioplastics to fossil-based plastics.*

| Petrochemical Plastics | Bioplastics Substitutes | Source |
|---|---|---|
| LDPE | Bio-PE, Bio-LDPE, PBAT, PHA, PLA, TPS, PHB | (Brizga et al. 2020; Zuiderveen et al. 2023; European Commission 2019) |
| PP | Bio-PP, PHB, Bio-PTT, PBS, PHA, PLA, TPS | (Brizga et al. 2020; Zuiderveen et al. 2023; European Commission 2019; Ali et al. 2023) |
| HDPE | Bio-PE, PBAT, PHA, PHB, PLA, TPS, Bio-HDPE | (Brizga et al. 2020; Zuiderveen et al. 2023) |
| PET | Bio-PET, Bio-PTT, PHA, PLA, PBS, PHB | (Brizga et al. 2020; Zuiderveen et al. 2023; European Commission 2019; Ali et al. 2023) |
| PS | PHA, PLA, TPS, PHB, PBS | (Brizga et al. 2020; Zuiderveen et al. 2023; European Commission 2019) |
| PVC | Bio-PVC, PHA | (Brizga et al. 2020) |
| PS expanded | TPS | (Brizga et al. 2020) |
| PA | Bio-PA, Bio-PTT | (Brizga et al. 2020) |
| PE | Bio-PE | (Zuiderveen et al. 2023; Ali et al. 2023) |
| PBT | PHLA | (Zuiderveen et al. 2023) |

### 3.2.2 Positive and Negative Environmental Impacts

A review by Ali et al. (2021) comparing bioplastics and fossil-based plastics reveals that bioplastics can have lower environmental impacts compared to fossil-based plastics i.e., PLA can have reduced impacts due to less energy consumption. Meanwhile, PBS from food waste can have significantly lower GHG emissions than fossil-based 1,4-Butanediol (Rajendran and Han 2023; Tecchio et al. 2016). Similarly, starch-based polymers (SBPs) have low NREU (60%) and GWP (80%), except for eutrophication potential and land use (Gironi and Piemonte 2011; Shen and Patel 2008). Bio-PE can also reduce GHG emissions by up to 140% and NREU by 65% compared to fossil-based PE (Tsiropoulos et al. 2015).
Brizga et al. (2020) extensively reviewed fossil-based and biobased plastics' environmental impacts. The results show that bioplastics can have a significant reduction in GWP. However, in some cases, the results show that biobased plastics (Bio-PP, Bio-PE) lead to negative impacts of GWP compared to counter fossils-based plastics. A meta-analysis by Weiss et al. (2012) reveals that substituting fossil-based plastics with bioplastics can reduce non-renewable energy use (NREU), climate change, and photochemical ozone formation. However, there is significant variation in the results because of the different methodological considerations in the studies.

Similar findings emerged in the meta-analysis conducted by Zuiderveen et al. (2023), which indicates that biopolymers can reduce up to 38% in GHG emissions (excluding biogenic carbon) and provide savings in NREU when replacing fossil based products. However, a contradiction arises regarding photochemical ozone formation. Zuiderveen et al. (2023) reports an increase in associated impacts, whereas the meta-analysis by Weiss et al. (2012) identified potential for reductions in these impacts. A detailed LCA study by the European Commission (2019) for seven case studies based on functional units (i.e., beverage bottles, cups, etc) reveals that biobased plastics can have overall environmental benefits compared to fossils based on climate change and abiotic depletion potential. Furthermore, the results regarding photochemical ozone formation and terrestrial eutrophication are inconclusive. Some bioplastics, such as bio-PET bottles, biobased carrier bags, PLA cups, films, and cutlery, do not show impact reductions. In contrast, other biopolymers, like biobased mulch films and clips, exhibit lower impacts when in-situ soil biodegradation is assumed as their end-of-life waste management method (European Commission 2019).
The meta-analysis by Zuiderveen et al. (2023) finds that there is very little difference in GHGs (excluding biogenic carbon) impact variation of BBPs, including biopolymers, with changing the feedstocks categories (first, second generation) (European Commission 2019) and TRL. Similarly, biopolymers' GHG emissions (excluding biogenic carbon) revealed net savings compared to fossil-based polymers, including or excluding the land use change in the evaluation of impacts (Zuiderveen et al. 2023).

Bioplastics could increase the impact of pesticides and chemical fertilisers during crop cultivation and have higher ozone layer depletion potential than fossil-based plastics (Ali et al. 2023). Similarly, the review by Gerassimidou et al. (2021) reports based on (Chen et al. 2016; Alvarenga et al. 2013; Brentrup et al. 2004) that fertilisers used in feedstock growing can lead to higher acidification, eutrophication potential, water pollution and habitat degradation. Deforestation and intensive agriculture driven by increased biomass feedstock cultivation can degrade land quality and agricultural productivity, thus impacting food security (Rafiaani et al. 2018). When produced from corn, PLA and TPS can have a higher acidification potential than petrochemical plastics. This is due to the wastewater generated during starch production and the use of plasticisers in the polymerisation process (Hottle et al. 2013).

The sustainability matrix created by Gerassimidou et al. (2021) shows that most of the impact categories such as land use change, ecosystem quality degradation, eutrophication and acidification for biobased plastics in the packaging sector has negative environmental impacts during the feedstock extraction phase, however GWP is controversial. The impacts associated to the biorefining or manufacturing stage is mostly dependent on the feedstock type as different feedstock can have different production processes, hence different energy demand and hence varying environmental impacts. Regarding the environmental assessment during the manufacturing and use phase, this study (Gerassimidou et al. 2021) finds huge blind spots in deciding whether or not biopolymers are more environmentally friendly than their fossil counterparts. Similarly, considering mechanical recycling as an EoL strategy, bioplastics have higher GWP, land use change, and ecosystem quality degradation compared to fossil-based plastics; however, it has less fuel depletion potential (Gerassimidou et al. 2021).

Similarly, a review by Brizga et al. (2020) also reports that substituting fossil-based plastics with bioplastics can lead to adverse environmental burdens. For example, it leads to higher land use and higher water use. Furthermore, a meta-analysis reveals that bioplastics can lead to higher eutrophication, acidification (Zuiderveen et al. 2023; Weiss et al. 2012), stratospheric ozone depletion (Weiss et al. 2012), ozone depletion and photochemical ozone formation (Zuiderveen et al. 2023).

### 3.2.3 Circular Economy

According to the EU waste hierarchy for plastics, including bioplastics, prevention and reuse should be kept in mind by improving the manufacturing process and material used to minimise resource exploitation (European Bioplastics e.V. 2024b). Bioplastics can be treated in already established recycling and recovery streams and offer additional options such as organic recycling (European Bioplastics e.V. 2024c). Besides these general EoL options, LCA studies show that most EoL options employed for fossil-based plastics can be employed for bioplastics.

Most of the bioplastics can have a variety of EoL options (Table 3-2). However, these EoL options can vary, and no one-fits-all solution exists. It depends upon the specific application, location, available waste management, collection and sorting system, technologies available and market value of the product (European Bioplastics e.V. 2024c).

*Table 3-2: End-of-life options and market application of different biobased polymers.*

| **Bioplastics** | **Market applications** | **EoL options** | **Suitable EoL option** | **Source** |
|---|---|---|---|---|
| PLA | Packaging (food), electronic components, 3D printing materials, other consumer goods, Tissue engineering, agriculture, biomedicine, single-use cups for cold drinks, single-use cutlery | Biodegradable, Composting (industrial), Recycling (mechanical and chemical), Landfill, Incineration, Anaerobic digestion | Recycling, Industrial Composting, Anaerobic digestion | (Ali et al. 2023; Reichert et al. 2020; Molina-Besch 2022; Ferreira-Filipe et al. 2021; Wellenreuther and André Wolf 2020; European Commission 2019) |
| PBS | packaging, agricultural mulch films, biomedicine, hygiene products | Biodegradable, Industrial Compostable, Recycling (chemical/catalytic) (all), Landfill, Incineration, Depolymerization (enzymatic) | Recycling | (Ali et al. 2023; Reichert et al. 2020; Ferreira-Filipe et al. 2021; Spierling et al. 2020) |
| CA | Textiles | Biodegradable, Compostable, Recycling, Landfill | Anaerobic digestion, Composting | (Ali et al. 2023) |
| SBPs | Textiles, Packaging, Pharmaceuticals, biomedicine, single-use clips, agriculture mulching films | Biodegradable, Compostable, Landfill, incineration | Biodegradation, Industrial composting | (Ali et al. 2023; European Commission 2019) |

*Table 3-2 (continued)*

| | | | | |
|---|---|---|---|---|
| Bio-PET | packaging, fibres, bottles (beverages), medicines | Biodegradable/Non-biodegradable, Compostable, Recycling, Landfill, Incineration, enzymatic depolymerisation | Recycling | (European Commission 2019; Ali et al. 2023; Ferreira-Filipe et al. 2021) |
| Bio-PE | packaging, automotive applications, toy production, cosmetics, agricultural applications, personal care | Biodegradable/Non-biodegradable, Compostable, Recycling (mechanical), Landfill, Incineration | Recycling | (Gerassimidou et al. 2021; Ferreira-Filipe et al. 2021; Ali et al. 2023) |
| PHA | packaging, agricultural, medical | Composting (Industrial + home), Incineration, Landfill, Recycling (all), Anaerobic digestion | Recycling | (Spierling et al. 2020; Reichert et al. 2020; Molina-Besch 2022; Ferreira-Filipe et al. 2021; Wellenreuther and André Wolf 2020) |
| PEF | packaging | Non-biodegradable, Recycling, enzymatic depolymerisation | Recycling | (Gerassimidou et al. 2021; Reichert et al. 2020; Ferreira-Filipe et al. 2021) |
| TPS | - | Landfill, Incineration, Recycling, Composting (industrial + home), Anaerobic digestion | Recycling | (Spierling et al. 2020; Molina-Besch 2022) |
| PHB | packaging, agriculture, medical | Biodegradable, Composting (industrial + home), chemical recycling, anaerobic digestion | Anaerobic digestion, Composting | (Ferreira-Filipe et al. 2021; Wellenreuther and André Wolf 2020) |
| Bio-PA11 | automotive and fuel tubing, electrical components, coatings | Non-biodegradable, Recycling (chemical + mechanical) | Recycling | (Gerassimidou et al. 2021; Ferreira-Filipe et al. 2021) |
| Bio-PP | - | Non-biodegradable, Recycling (mechanical) | Recycling | (Ferreira-Filipe et al. 2021) |
| Bio-LDPE | single-use carrier bags | Recycling, Incineration, Landfilling | Recycling | (European Commission 2019) |

*Table 3-2 (continued)*

| | | | | |
|---|---|---|---|---|
| Bio-HDPE | - | Recycling, Incineration | Recycling | (Spierling et al. 2020) |

Regarding EoL options, most LCA studies emphasise organic recycling, mainly composting and anaerobic digestion (AD), as suitable disposal methods for biodegradable bioplastics, especially PLA (Ali et al. 2023; Gerassimidou et al. 2021). Studies suggest that biogas from PLA degradation in AD systems can substitute natural gas, reducing GHG emissions by up to 55% if digestate is used as a fertiliser (Staffell et al. 2019; Hermann et al. 2011; Rossi et al. 2015; Flury and Narayan 2021). However, composting as an EoL solution remains debatable for biodegradable plastics, as it may not be inherently sustainable but offers an alternative to landfilling, which poses more significant environmental risks (Ali et al. 2023).

Mechanical recycling, particularly for non-biodegradable bioplastics, is more sustainable than other EoL options (Gerassimidou et al. 2021; Changwichan et al. 2018; Piemonte and Gironi 2012; Maga et al. 2019; Rossi et al. 2015). PLA ranks highest in recyclability among bioplastics, followed by PP, PBS, and PHAs, as mechanical recycling of PLA reduces raw material consumption, minimises carbon emissions, and lowers energy demand (Gerassimidou et al. 2021). While chemical recycling holds potential, its large-scale feasibility remains limited (Soroudi and Jakubowicz 2013; Faisal et al. 2006). Incineration with energy recovery is a viable alternative but is less favourable than recycling due to its higher GHG emissions and energy consumption, though preferable to landfilling (Gerassimidou et al. 2021; Rujnić-Sokele and Pilipović 2017). Overall, a combination of anaerobic digestion, mechanical recycling, and energy recovery appears to be the most viable approach for biopolymer waste management. However, further comparative analyses are needed to optimise EoL strategies against environmental and economic trade-offs (Ali et al. 2022).

However, EoL solutions for bioplastics should be thoroughly investigated and compared to the advantages of other existing materials and EoL procedures. EoL options and associated best sustainable options available for biopolymers are presented in Table 3.2. This information was collected based on weighted results of the impacts calculated in (European Commission 2019) and the GWP impacts of biopolymers from (Spierling et al. 2020). If no information is available, information from (Ali et al. 2023; Gerassimidou et al. 2021) was used. However, more studies are needed to evaluate further EoL impacts associated with each option, as trade-offs seem to be evident, e.g. mechanical recycling of PLA has a low GWP value but high acidification and eutrophication values (Figure 3-3, Figure 3-4, Figure 3-5).

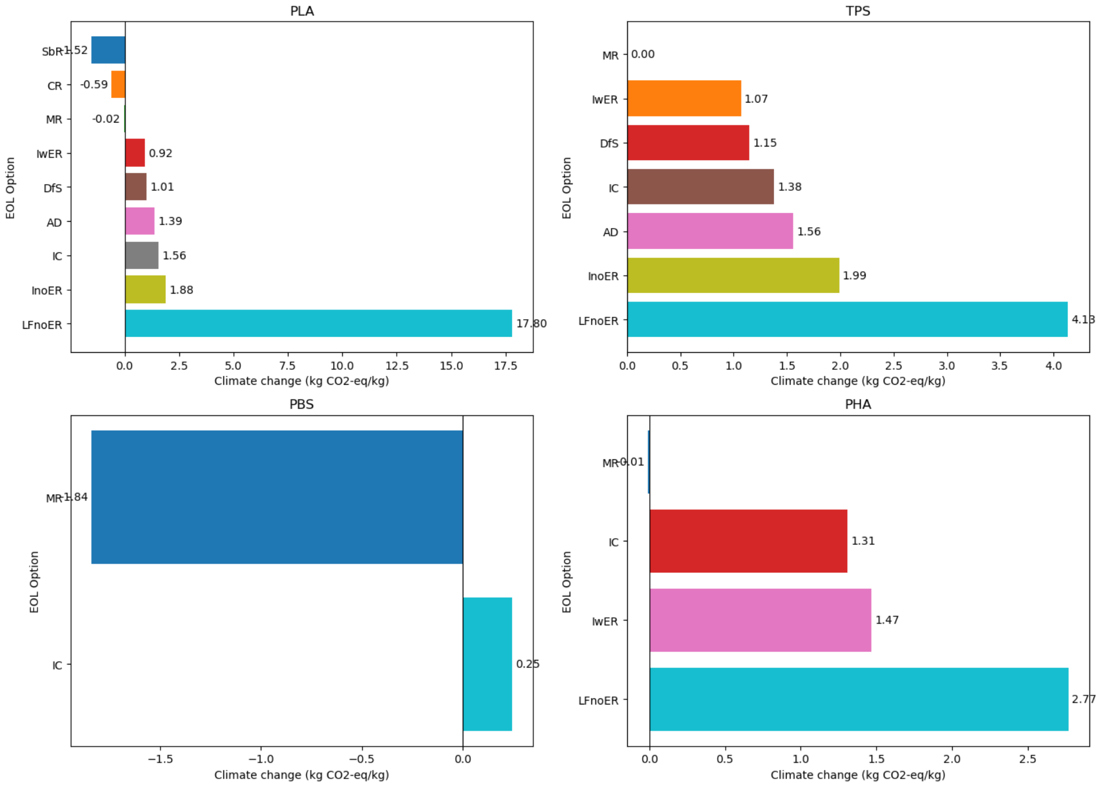


*Figure 3-3: EoL options and associated average GWP impacts of biopolymers MR: mechanical recycling, CR: chemical recycling, SbR: solvent-based recycling, IC: industrial composting, DfS: direct fuel substitution in plants, IwER: incineration with energy recovery, InoER: incineration without energy recovery, AD: anaerobic digestion, LFnoER: landfill without energy recovery, LFwER: landfilling with energy recovery (data source: (Spierling et al. 2020)).*

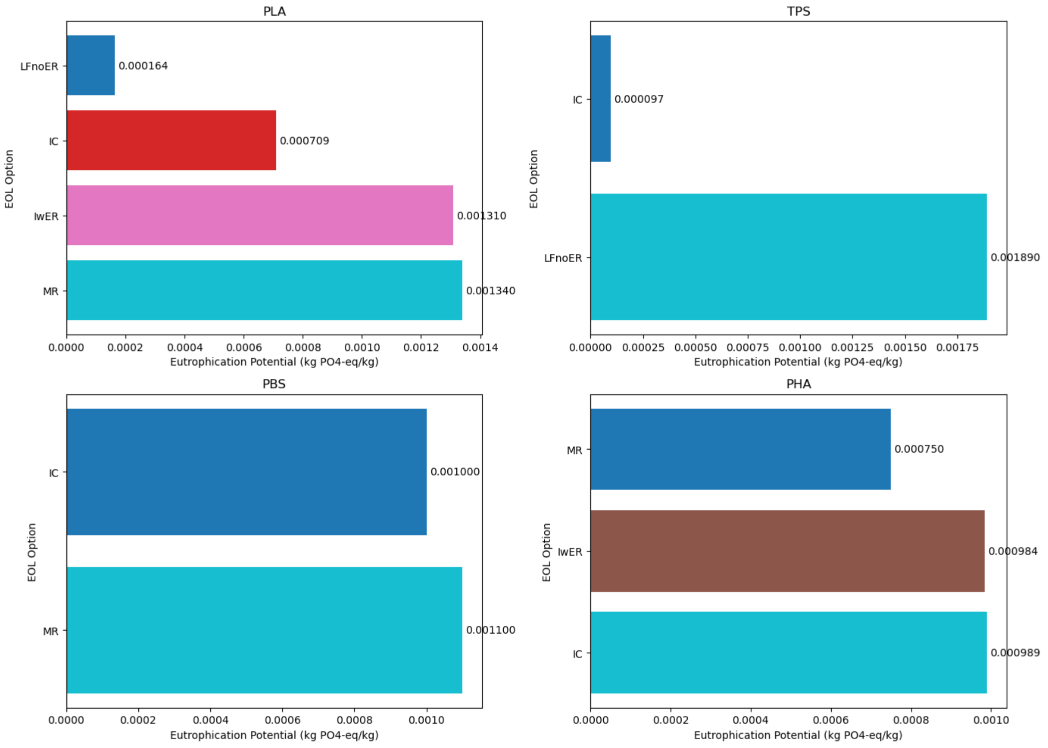


*Figure 3-4: Average eutrophication potential impacts associated with EoL options for biopolymers (data source: (Spierling et al. 2020)).*

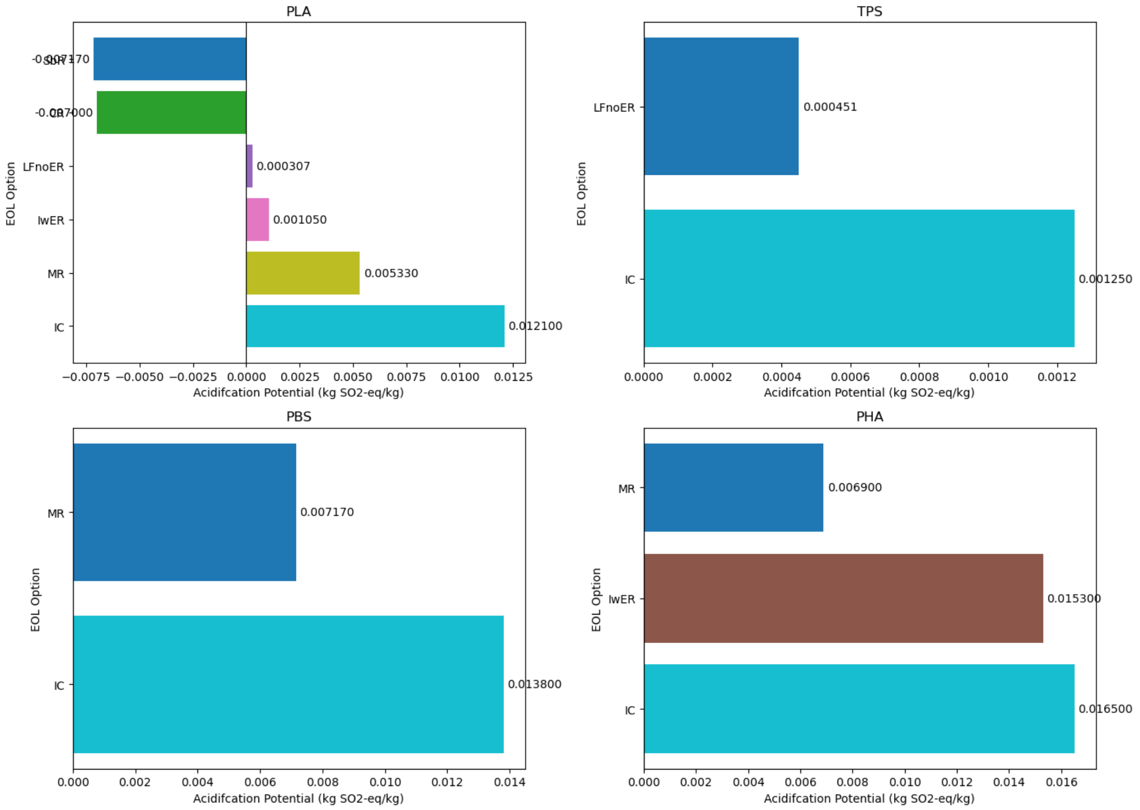


*Figure 3-5: EoL options and associated average acidification potential impacts of biopolymers (data source: (Spierling et al. 2020)).*

### 3.2.4 Hotspots Analysis

Conversion of biomass to bioplastics is an energy-intensive process and, hence, the primary hotspot in biopolymer manufacturing, i.e., during conversion of lactic acid to PLA, 50% of impacts are energy-related emissions (Ali et al. 2023; Rajendran and Han 2023; Kang et al. 2021; Rezvani Ghomi et al. 2021; Gerassimidou et al. 2021).

A detailed LCA study by the (European Commission 2019) for biopolymers based on their functional unit for different end-use applications reveals that the highly energy-intensive manufacturing phase is responsible for almost 50% of the total impacts in cradle-to-grave system boundary, which arises from the high amounts of electricity, heat, and chemicals in this phase (European Commission 2019). The biomass production phase is responsible for at least 10% of the overall impacts, while transportation has negligible impacts in most of the case studies of biopolymers.

### 3.2.5 Environment Performance Matrix

Based on the review and meta-analysis studies, we created an environmental performance matrix (Table 3-3) Although it can not provide a precise overview of complete environmental sustainability, there are common environmental benefits reported in almost all reviews and meta-studies, such as for climate change, NREU and abiotic depletion based on large samples of data. Therefore, this matrix provides at least a positive environmental performance of bioplastics compared to fossil-based plastics in some impact categories.

*Table 3-3: Environmental assessment matrix for assessing biobased plastics in comparison to fossil-based plastics. Green box: biobased plastics have fewer impacts compared to fossil-based plastics, red box: biobased plastics with higher impacts, grey box: impact category is not explicitly mentioned or unclear; impact categories (GWP Global warming potential, EP; Eutrophication potential, AP; Acidification potential; NREU; Non-renewable energy use, AD; abiotic depletion; LU; Land use; WU; Water use, PM; particulate matter; TOF; Terrestrial ozone formation; POF; Photochemical ozone formation; SOD; Stratospheric ozone depletion).*

| Source | GWP | EP | AP | NREU | AD | LU | WU | PM | TOF | POF | SOD |
|---|---|---|---|---|---|---|---|---|---|---|---|
| (Ali et al. 2023) | 🟩 | 🟥 | ⬜ | 🟩 | 🟩 | 🟥 | ⬜ | ⬜ | ⬜ | ⬜ | ⬜ |
| (Gerassimidou et al. 2021) | ⬜ | 🟥 | 🟥 | ⬜ | ⬜ | 🟥 | 🟥 | ⬜ | ⬜ | 🟥 | 🟨 |
| (Brizga et al. 2020) | 🟩 | ⬜ | ⬜ | ⬜ | ⬜ | 🟥 | 🟥 | ⬜ | ⬜ | ⬜ | ⬜ |
| (Weiss et al. 2012) | 🟩 | 🟥 | ⬜ | 🟩 | ⬜ | ⬜ | ⬜ | ⬜ | ⬜ | 🟩 | 🟥 |
| (Zuiderveen et al. 2023) | 🟩 | 🟥 | 🟥 | 🟩 | ⬜ | ⬜ | ⬜ | ⬜ | ⬜ | 🟥 | 🟨 |
| (European Commission 2019) | 🟩 | ⬜ | ⬜ | ⬜ | 🟩 | ⬜ | ⬜ | 🟥 | 🟥 | 🟥 | ⬜ |
| Overall Impacts | 🟩 | 🟥 | 🟥 | 🟩 | 🟩 | 🟥 | 🟥 | 🟥 | 🟥 | 🟥 | 🟥 |

### 3.2.6 Uncertainty Factors and Recommendations

There is enormous uncertainty and ranges of environmental impacts for individual polymers in different impact categories mentioned by many review studies, making it difficult to make decisions and derive conclusions about the environmental sustainability assessment. The important factors are biogenic carbon accounting methodological differences, lack of data, different LCA parameters, lack of harmonisation, unreliable comparisons, impacts of indirect land use changes and differences in LCI data. These factors lead to uncertain results or significant variations in the environmental impact assessments.

Similarly, review papers and meta-analysis studies identified some potential recommendations to further improve environmental performance and circularity, including recommendations for harmonised studies to support decision-making. These include using variable feedstocks for manufacturing BBPs, evaluating complete sustainability assessments, using sustainable agricultural practices, further improving technological innovation, using a green energy mix and further LCA research in the BBPs sector to improve the environmental performance and drawing precise conclusions.

### 3.2.7 Critical Aspects

The environmental assessment of biobased plastics does not yet have a clear picture of whether they are more environmentally friendly than fossil-based alternatives. Most of the review studies and meta-analyses report environmental benefits in terms of climate change, NREU and abiotic depletion (fossil fuels). However, they also have negative consequences in terms of eutrophication and acidification. Reviews and metanalysis studies (Ali et al. 2023; Gerassimidou et al. 2021; Brizga et al. 2020; Zuiderveen et al. 2023) do not provide explicit statements on the environmental sustainability of biobased plastics due to many methodological challenges and uncertainty factors.

#### 3.2.7.1 Scope Definition

It is difficult to conclude the environmental performance of biobased plastics based on the available review papers, especially quantitatively. If the scope of the review studies is feedstock specific, i.e., focused on first-generation feedstock biopolymers (e.g. (Gerassimidou et al. 2021)), the impacts associated with acidification and eutrophication will be high due to the use of fertilisers and chemicals for biomass production.

Mostly, the geography of the manufacturing stage, which is the primary hotspot in the bioplastic life cycle, is missing (Table 4-1). Furthermore, the scope of some reviews and meta-studies

(Brizga et al. 2020; Weiss et al. 2012) does not consider the system boundary, geographical scopes, technological readiness level, allocation methods, functional unit, biogenic carbon accounting (Table 4-1), which creates blind spots while assessing the environmental performance of biobased plastics.

#### 3.2.7.2 GWP Reporting

EN 15804 (2022) standard recommends calculating the climate change impact category separately, as GWP-fossil, GWP-biogenic and GWP-luluc. Although this standard focuses on construction products, it applies to other BBPs. However, while reporting GWP, most studies do not clearly report the GWP separately. This could lead to uncertainties and incorrect interpretation of the climate change impacts of BBPs. Therefore, LCA practitioners should follow (EN 15804 2022) requirements to ensure comparability, consistency, and accurate benchmarking by reporting all three GWP indicators separately.

#### 3.2.7.3 Function and Substitution Potential

Moreover, most of the studies reviewed present results based on the declared unit or without accessing the substitution potential of biobased polymers (Table 3-1) for fossil-based polymers, except (European Commission 2019). This further leads to uncertainty in the results and comparison. The metanalysis by Zuiderveen et al. (2023) comparing emerging technologies with conventional technologies is based on upscaled foreground processes. At the same time, future background changes are not integrated, such as changes in electricity mix composition and their efficiencies. The impact could be significantly different since energy is a major hotspot in biobased plastics.

A significant issue in the literature is that most review papers emphasise the declared unit (Polymer/kg) rather than the functional unit or the end product when comparing biobased plastics with fossil-based plastics. This practice may lead to either overestimating or underestimating their respective environmental impacts. The study conducted by the European Commission (2019) has indicated that, due to varying mechanical and chemical properties, the weight necessary to achieve a functional unit (bottle or cup) is not precisely the same for biobased and fossil-based plastics, i.e., in the case of FU of clips for agriculture purpose, 72 kg of biobased clips (starch plastics) and 54 kg of fossil-based (PP) clips are required.

## 3.3 Environmental and Circularity Assessment of Biochemicals

### 3.3.1 Overview of Biochemicals

The biobased chemical sector represents the fourth largest industrial sector within the EU based on sales volume (Rinke Dias de Souza et al. 2024). Among the various subsectors, the most significant production shares are attributed to platform chemicals, polymers for plastics, paints, coatings, inks, and dyes (JRC et al. 2019). The predominant biobased chemicals produced within these sectors are lactic acid, succinic acid, and furfuryl alcohol (Rinke Dias de Souza et al. 2024). Although GHG emissions from the production sector have substantially decreased over the past few decades, the chemical sector must undertake considerable efforts to reduce approximately 60 million tons of GHG emissions to meet climate change mitigation objectives and achieve net-zero emissions. The environmental performance of biochemicals depends upon the method used for the assessment, biomass feedstock usage, industrial conversion, and end-of-life. However, biochemicals can provide environmental benefits compared to fossil-based counterparts (Rinke Dias de Souza et al. 2024).

### 3.3.2 Positive and Negative Environmental Impacts

Biobased chemicals can significantly reduce climate change impacts and NREU (Weiss et al. 2012; Zuiderveen et al. 2023). Almost all biochemicals reviewed in the meta-analysis study (Weiss et al. 2012) showed environmental benefits for these two impact categories (climate change, NREU) except acidic acid, which shows a higher value compared to fossil-based chemicals. The meta-analysis by Zuiderveen et al. (2023) reveals that replacing the primary petrochemicals butadiene and ethylene could potentially save up to 19% of GHG emissions. However, there are potential trade-offs with impacts like eutrophication, acidification, ozone depletion and photochemical ozone formation. In contrast, a review by Ögmundarson et al. (2020) reports that land use and acidification impacts of biochemical results are either not very decisive or may also perform worse than fossil-based chemicals. Furthermore, this study by Ögmundarson et al. (2020a) found that while biobased chemicals exhibit low climate change and non-renewable cumulative energy demand, they exhibit higher impacts related to land use and eutrophication potential. However, this is not true for all chemicals; for example, lactic acid production has lower environmental impacts in most impact categories except land usage and water use (Ögmundarson et al. 2020a). Similar insights are reported in the review study by Fiorentino et al. (2017), which reports that the characterised and normalised impacts of biobased ethyl levulinate have significantly lower GWP, human toxicity potential, metal depletion potential, and fossil depletion potential than counter fossil-based ethyl acetate.

Furthermore, the climate change and NREU impacts are subject to variation based on the feedstock utilised, i.e., the GWP of hexanoic acid is lower when produced from sugar cane bagasse compared to corn stover as the feedstock (Figure 3-6). Similarly, lactic acid has lower GWP than counter fossil-based chemicals when manufactured from corn but higher GWP when manufactured from corn stover. Fiorentino et al. (2017) also report that the normalised GWP impacts of biobased ethyl levulinate from waste wood have a lower value as compared to those manufactured from agro-residues.

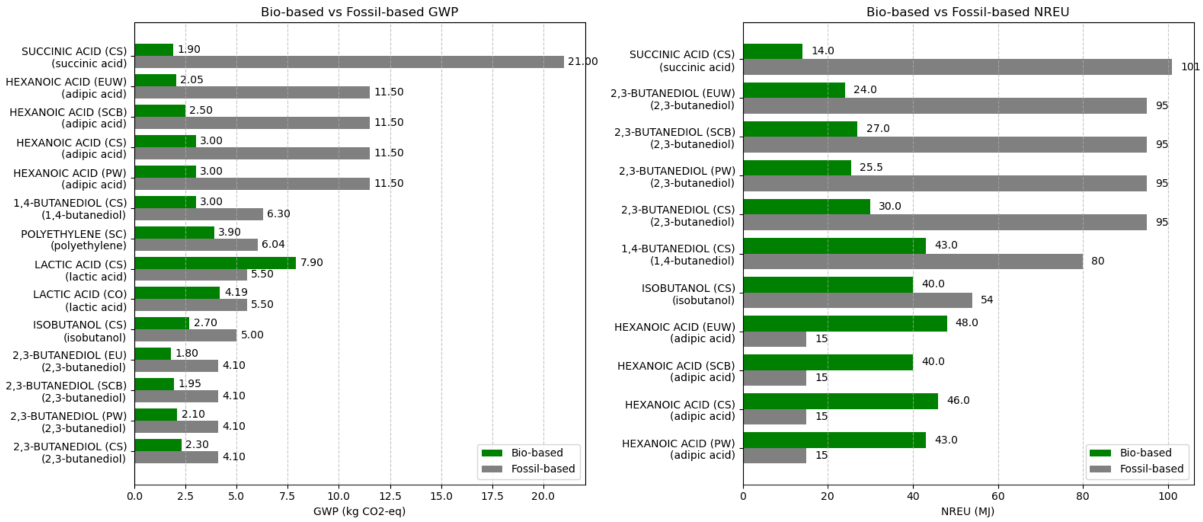


*Figure 3-6: Average climate change and NREU impacts in cradle-to-grave system boundary related to biochemicals and fossil-based chemicals (EUW; Eucalyptus wood, SCB; Sugar cane bagasse, SC; sugar cane, PW; pine wood, CS; corn stover; CO; corn)(conversion process for all chemicals is biological (biochemical) conversion except 1,4-butanediol which is thermochemical conversion (data source: (Zuiderveen et al. 2023)).*

Significant variations exist in the impacts of bio-based chemicals, which are influenced by multiple factors, including the type of biomass feedstock employed. This selection subsequently affects the conversion process and its associated energy intensity. Furthermore, even when identical feedstock and conversion processes are applied, discrepancies may arise in managing multifunctionality and the energy mix utilised for modelling purposes. For example, the GWP of lactic acid ranges from -0.2 to 0.6 kg $CO_2$-eq per kg of product despite using the same feedstock (corn stover) and conversion process (hydrolysis and fermentation) (Figure 3-7).

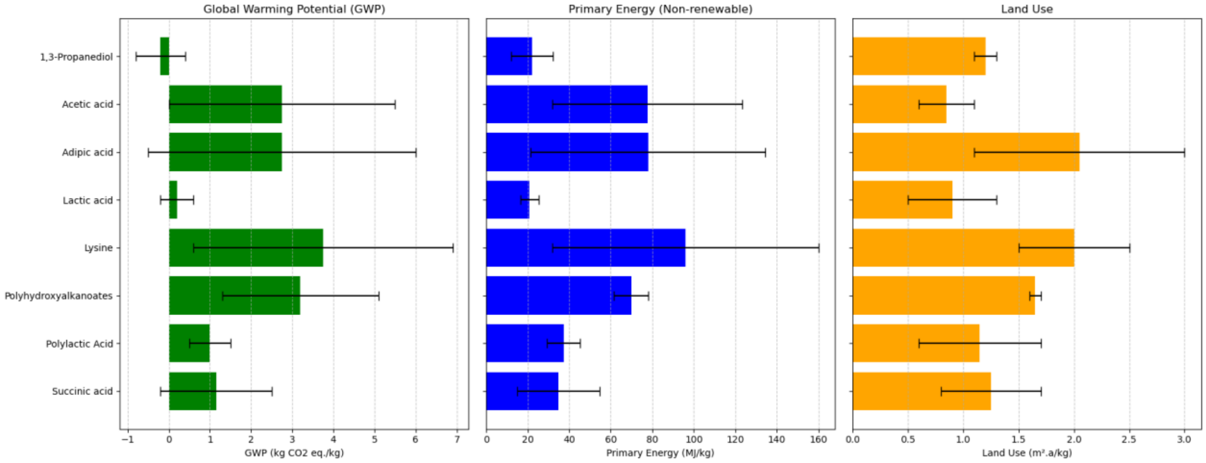


*Figure 3-7: Cradle-to-gate ranges of environmental impacts of biobased chemicals in the EU geography. Error bars show minimum and maximum values, while the bars show the average value of environmental impacts (data source: (JRC et al. 2018)).*

The impact category of land use shows variations, on the one hand, to methodological choices in LCA, on the other hand, to crop used, feedstock obtained from it, and its yield per hectare for the production of biochemicals production (JRC et al. 2019). For example, biobased chemicals that are made from castor oil only, i.e. sebacic acid, ricinoleic acid, azelaic acid, polyamide 11, and polyamide-4,10, require more land because of the lower yield per hectare compared to other oils crops. Palms have higher seed yields compared to other crops such as soybean, rapeseed, and caster beans, and hence, products made from palm oil have three times less land usage than products that are made from other dedicated vegetable oil crops, i.e., castor oil (JRC et al. 2019).

### 3.3.3 Circular Economy

Most review studies on biochemicals do not precisely reflect on EoL or circularity assessments despite their importance in sustainability evaluation. Although some platform chemicals and polymers used to make bioplastics are already discussed in the bioplastics section. However, the comparative assessment of EoL of biobased and fossil-based chemicals remains limited (Ögmundarson et al. 2020a; Eisen et al. 2020).

Ögmundarson et al. (2020a) conducted a comparative analysis of the EoL impacts of biobased chemicals vs fossil-based chemicals, revealing that EoL impacts of biobased chemicals are comparatively high compared to fossil-based products, but these impacts vary mainly due to differences in geographical and cultural waste treatment practices. The study highlights the diverse waste disposal options for biochemicals, such as industrial composting, incineration (with or without heat recovery), and landfilling (Ögmundarson et al. 2020a). A key concern is that biodegradable chemicals are often claimed to be $CO_2$ emission neutral, yet methane emissions from landfilling can offset these benefits (Ögmundarson et al. 2020a). Thus, an accurate EoL assessment must consider realistic disposal scenarios to prevent misleading conclusions about the actual environmental impacts of BBPs (Ögmundarson et al. 2020a).

#### 3.3.3.1 Role of Biorefineries in Circular Economy Integration

Ioannidou et al. (2020) critically discuss the role of biorefineries in enabling a circular economy for bio-based chemicals, emphasising the potential for integrating industrial and food supply chain side streams into bioprocessing in biorefineries. The study highlights that sustainable production of biochemicals relies on optimising the use of renewable feedstocks such as agricultural residues, forestry waste, and food processing side streams. The study highlights vast opportunities in the EU to utilise these industrial and food supply chain side streams, such as fruit and vegetable side streams, by-products from breweries and wineries, sugar beet pulp, spent coffee grounds, crude glycerol, spent liquors from pulp and paper industry, organic fraction of municipal solid wastes for manufacturing of biobased chemicals.

The conventional linear production and consumption model, which relies on continuous growth and increasing resource throughput, poses serious challenges. However, the circular production model, by integration of these industrial and food supply chain side streams into biorefineries, enables the cascading use of resources, reducing dependency on fossil-based alternatives while minimising waste generation (Ioannidou et al. 2020).

A robust circularity assessment requires evaluating techno-economic feasibility, environmental sustainability, and social impacts to ensure that bio-based chemicals and polymers truly align with circular economy principles. Key factors to consider are assessing end-of-life scenarios, resource efficiency, and LCA methodologies to compare the sustainability performance of bio-based and fossil-based alternatives (Ioannidou et al. 2020).

Furthermore, Ioannidou et al. (2020) conclude that the implementation of circular economy principles in bio-based chemical production requires a thorough evaluation by selecting the most appropriate EoL scenarios to mitigate burden shifting and to facilitate a genuinely sustainable transition from fossil-based to bio-based products. Furthermore, the development of dedicated chemicals can bring more environmental advantages than their fossil counterparts in terms of recyclability, biodegradation and lower toxicity (Rinke Dias de Souza et al. 2024).

### 3.3.4 Environmental Performance Matrix

The sustainability assessment of biobased chemicals does not provide absolute environmental sustainability because fertilisers and agricultural inputs are used for feedstock growing. However, it is difficult to come to a conclusion on whether biobased chemicals are more sustainable than fossil-based ones because the review and meta-analysis studies don’t provide a complete picture for comparison. There are many uncertainties in the sustainability assessment reported by these studies, as shown in Table 3-4.

However, due to all these differences, we tried to make a sustainability matrix to show at least the commonalities among these studies. Biochemicals observed advantages in categories such as GWP, NREU, and HTP, suggesting that bio-based alternatives can reduce climate change impacts and reliance on fossil resources. In contrast, acidification, eutrophication, and stratospheric ozone depletion show increased environmental burdens in some studies. These negative impacts can arise from land-use change and agricultural inputs such as fertilisers and pesticides.

When discussing the various methodological differences and uncertainties highlighted in the literature, particularly in review and meta-analysis studies, several common conclusions emerge. It is clear that biobased chemicals have the potential to significantly reduce climate change impacts and decrease reliance on non-renewable energy sources. There are also reported trade-offs, but the existing data on these trade-offs lacks sufficient depth to support definitive conclusions. Therefore, there is a critical need for more comprehensive LCA research to accurately evaluate the sustainability of biobased chemicals compared to fossil-based alternatives.

Besides the potential benefits and trade-offs, there are still gaps in the literature regarding the assessment of all impact categories. This knowledge gap highlights the need for further research to comprehensively analyse these categories, providing a clearer understanding of both the benefits and trade-offs of bio-based chemicals. A more complete assessment is essential to draw definitive conclusions about the absolute environmental sustainability of bio-based chemicals compared to their fossil-based counterparts.

*Table 3-4: Environmental sustainability matrix for assessing biobased chemicals in comparison to fossil chemicals; the green box means the study found biobased polymers have fewer impacts, the red box represents higher impacts related to fossil-based plastics, and the grey box represents that the impact category is not explicitly mentioned or unclear (GWP; Global warming potential, EP; Eutrophication potential, AP; Acidification potential; NREU; Non-renewable energy use, AD; abiotic depletion; LU; Land use; WU; Water use, PM; particulate matter; TOF; Terrestrial ozone formation; POF; Photochemical ozone formation; SOD; Stratospheric ozone depletion, HTP; Human toxicity potential.*

| Source | GWP | EP | AP | NREU | AD | LU | WU | PM | POF | SOD | HTP |
|---|---|---|---|---|---|---|---|---|---|---|---|
| (Weiss et al. 2012) | 🟩 | 🟥 | 🟩 | 🟩 | ▨ | ▨ | ▨ | ▨ | ▨ | 🟥 | ▨ |
| (Rinke Dias de Souza et al. 2024) | 🟩 | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ |
| (Zuiderveen et al. 2023) | 🟩 | 🟥 | 🟥 | 🟩 | ▨ | ▨ | ▨ | ▨ | 🟥 | 🟧 | ▨ |
| (Ögmundarson et al. 2020a) | 🟩 | 🟥 | 🟥 | 🟩 | 🟩 | 🟥 | 🟥 | 🟥 | ▨ | ▨ | ▨ |
| (Eisen et al. 2020) | 🟩 | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | 🟩 |
| (Ioannidou et al. 2020) | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ |
| (Fiorentino et al. 2017) | 🟩 | ▨ | ▨ | 🟩 | 🟩 | 🟥 | 🟥 | ▨ | ▨ | ▨ | 🟩 |
| Overall impacts | 🟩 | 🟥 | 🟥 | 🟩 | 🟩 | 🟥 | 🟥 | 🟩 | 🟥 | 🟥 | 🟩 |

### 3.3.5 Uncertainty Factors and Further Recommendations

There are ranges of environmental impacts identified in the literature regarding the environmental impacts of biobased chemicals, which makes it difficult to draw precise conclusions and support decision-making. These factors include different energy mixes used for modelling, EoL treatment, biogenic carbon accounting, and different LCA methodologies. Furthermore, differences in FU, system boundaries, and allocation methods used further complicates the issue. Furthermore, different choices of LCIA methodology and spatial variability in the impacts also lead to varying results.

To address the challenges regarding uncertainties, targeted recommendations are proposed to further enhance environmental sustainability and circularity and improve methodological choices in order to get precise conclusions that support decision-making. These recommendations range from LCA integration in the early stages of development, using alternative feedstocks, using integrated biorefinery concepts by integrating biochemicals with biofuels and bioenergy and defossilizing the chemicals sector through sustainable hydrogen integration. Furthermore, the development of dedicated biobased chemicals, improving the data availability and databases, and standardising LCA methodology will help conduct more accurate sustainability assessments for decision-making.

### 3.3.6 Critical Aspects

#### 3.3.6.1 GWP Reporting

While reporting GWP, most studies do not clearly separate the GWP into its components, i.e., GWP (fossil, biogenic, land use and land use change (luluc)), despite the fact that EN 15804 (2022) standard (for construction products) states that GWP should be declared separately. This also applies to other BBPs because such impacts are important to consider in terms of climate change impacts. Therefore, LCA practitioners should follow (EN 15804 2022) requirements to ensure comparability, consistency, and accurate benchmarking by reporting all three GWP indicators separately.

#### 3.3.6.2 Invalid Comparisons

Biochemicals present almost similar fates to bioplastics in terms of sustainability and circularity assessment. Most of the studies do not clearly report the system boundary and functional unit while comparing the biobased chemicals and fossil-based chemicals, which can significantly overestimate or underestimate these results. A review by Eisen et al. (2020) clearly mentioned that biobased adhesives may or may not have equal adhesive properties compared to fossil-based adhesives. Therefore, it is important to make valid comparisons for the same functional unit having the same system boundary. Hence, it is important to make comparisons on the basis of valid functional units.

#### 3.3.6.3 Environmental Trade-offs

Furthermore, the burdens or trade-offs associated with biobased chemicals, i.e., eutrophication and acidification, reported in the studies are based on very few samples of data as compared to the environmental benefits, i.e., climate change and NREU. For example, the trade-offs associated with biobased chemicals presented in meta-analysis studies by Zuiderveen et al. (2023) and Weiss et al. (2012) are based on a minimal number of sample data compared to huge samples of data assessed for climate change and NREU. Therefore, the burdens are still not clearly reported in many studies, and more research is needed to report such burdens clearly for decision-making in terms of sustainability assessment.

#### 3.3.6.4 EoL Consideration

While comparing the biobased vs fossil-based products, most studies do not report the EoL of the comparative products. The choice of the EoL option, however, leads to significant variation in the results (Ögmundarson et al. 2020a; Ioannidou et al. 2020). Although meta-analysis by Zuiderveen et al. (2023) considered incineration as the only EoL option for the assessment of biobased vs fossil-based products, this may lead to an overestimation of the impacts as recycling can substitute the product and get credits, further minimising the impacts. A review by Ögmundarson et al. (2020a) does include EoL comparison as well, but there are many grey areas for which there is no clear information available, and hence, it is challenging to make valid comparisons. These uncertainties across the comparative studies need more comprehensive LCA studies, particularly clearly mentioning the realistic EoL options and their impacts that should help in making valid comparisons of the biobased and fossil-based products.

#### 3.3.6.5 LCA Methodologies and Assumptions

Overall, the sustainability assessment of biobased chemicals in comparison to fossil-based chemicals is very decisive in making conclusions. The reason is that most of the studies do not take into consideration the LCA methodologies used, FU, system boundary, and geography of processing while collecting information. Furthermore, studies are mainly based on theoretical assumptions, as Zuiderveen et al. (2023) assumed incineration is an EoL option for products, which does not present an accurate picture of the impacts. A review by Eisen et al. (2020) also highlights this issue while reviewing bio adhesives LCA studies, that most of the environmental impacts reported in the studies are based on theoretical assumptions, and hence, it is not easy to derive conclusions about the sustainability assessments of biobased chemicals.

#### 3.3.6.6 Upscaling of Low TRL Products

Another issue is that most of the BBPs including biochemicals are at a lab scale, and comparing them with commercial-scale fossil-based products requires a cautious and harmonised approach to upscaling data to show realistic comparisons. Even if the LCI data is upscaled for emerging BBPs, as done in a meta-analysis by Zuiderveen et al. (2023), accurate prospective data might have a much different picture depending upon the future technologies, material and energy efficiencies and future electricity mixes. Eisen et al. (2020) report that this issue presents significant uncertainties while evaluating novel and emerging biobased value chains.

## 3.4 Environmental and Circularity Assessment of Traditional and Emerging Wood-based Products

### 3.4.1 Overview of Wood-based Products

As of 2021, the EU-27 has a total forest area of approximately 160 million hectares. For 2022, the total roundwood production in the EU-27 member states is estimated to be around 508.4 million cubic meters. The forestry sector plays a crucial role in contributing to BBPs in the EU, supplying at least 54% of its total end-use consumption to BBPs. The highest shares of this contribution come from the following industries: the sawn mill industry (22%), the pulp industry (17%), the panel industry (11%), and the wood pallet industry (approximately 4%) (Khan et al. 2024b). A review by van den Auwelant et al. (2024) for LCA of woodworking sectors (sawn wood, wooden construction materials, wood-based panels) reveals that LCA is applied to many woodworking sectors, but construction sectors are the dominant sector.

### 3.4.2 Positive and Negative Environmental Impacts of Wood-based Products

Environmental impacts of traditional wood-based products, as classified in (Khan et al. 2024a), are mostly reported without comparison to fossil-based or conventional materials providing the same functions. For example, the review by Costa et al. (2024) analysed LCA studies of wood-based panels, and the review by Cosentino et al. (2023) compared biobased insulation materials, including wood-based insulation materials. There are fewer studies directly comparing wood-based products to other functionally equal products; among them, the most extensive one is by Werner and Richter (2007), comparing wood-based products to other products made from other materials. The review by Deviatkin et al. (2019) compared wood and plastic pallets, and the meta-analysis by Weiss et al. (2012) reported floor boarding and biocomposites to conventional products. Similarly, the meta-analysis by Zuiderveen et al. (2023) reported wood plastic composites to fossil-based plastics. The main scope of this study is the comparison of environmental impacts to fossils, and hence, this is the main focus of the following paragraphs.

Werner and Richter (2007) conducted a comprehensive review of the environmental performance of wood-based products in comparison to functionally equivalent products made from other materials, such as windows, insulation materials, flooring, wall constructions, doorframes, furniture, railway sleepers, and utility poles. Their findings indicate that wood products generally exhibit a more favourable environmental profile when compared to functionally equivalent products derived from alternative materials. Specifically, wood-based products typically demonstrate reduced consumption of non-renewable energy and lower cumulative energy demand. Furthermore, the potential contributions of these products to the greenhouse effect and the quantities of solid waste generated are often minor or negligible in contrast to competing products. It is, however, noteworthy that wood products are frequently linked to greater consumption of renewable energy sources by virtue of their inherent characteristics.

#### 3.4.2.1 Construction

A review by van den Auwelant et al. (2024) reports that carbon emissions can be decreased by 13-26% by using wood in building materials instead of steel and concrete. Werner and Richter (2007) report that wood-based walls generally show better environmental performance in case of climate change and NREU. A study by Gustavsson et al. (2005) reveals that the production of materials for wood-framed construction emits less $CO_2$ and requires less energy in comparison to the production of materials for concrete construction.

#### 3.4.2.2 Insulation Materials

A review by Cosentino et al. (2023) comparing the biobased insulation materials for the functional units (1 $m^2$ with a thermal resistance of 2.5 $m^2k/W$) reveals that wood fibre insulation board shows lower GWP (including biogenic carbon) in comparison to conventional fossil-based materials, i.e., polyurethane rigid panel, and expanded polystyrene. A review by Füchsl et al. (2022) also reveals that cellulose-based insulation material (derived from recycled paper) has lower GWP and cumulative energy demand than counter-fossil-based products.

A study by Werner and Richter (2007) reveals that in the case of insulation materials, wood-based products, such as wood fibre board and cellulose fibres, demonstrate superior performance in various environmental impact categories compared to fossil-based insulation materials (like expanded polystyrene) and mineral-based products (such as glass wool, foam glass, and mineral wool). Specifically, wood-based products outperform in terms of non-renewable energy consumption, GWP, AP, EP, photochemical ozone formation, and human toxicity potential in cradle-to-gate system boundaries.

#### 3.4.2.3 Flooring, Windows, Doorframes

In the case of the flooring sector, Werner and Richter (2007) reports that wood-based flooring (parquet 3-layers) shows better performance in NREU and acidification potential compared to fossil-based (extruded PVC, PVC); however, they have higher impacts in eutrophication. Similar results are reported in a meta-analysis by Weiss et al. (2012) for floor boarding, showing a better environmental profile regarding climate change, NREU, eutrophication and acidification. However, trade-offs exist in tropospheric ozone formation.

Similarly, in case of windows and doorframes made of wood generally show better environmental performance in the case of NREU, cumulative energy demand, GWP, EP, photochemical ozone formation, and stratospheric ozone depletion potential (Werner and Richter 2007).

#### 3.4.2.4 Pallets

A review by Deviatkin et al. (2019) comparing the LCA of wood and plastic pallets reveals that the climate change impacts of plastic pallets are generally higher than those of wooden pallets. For European wood pallets, the carbon footprint ranged from -26 to 9.9 kg $CO_2$-equ per pallet. For plastic pallets, estimates ranged from 22 to 166 kg $CO_2$-equ per pallet when using virgin plastic and from 3.7 to 4.1 kg $CO_2$-equ per pallet when using recycled plastic. The utilisation of waste plastic significantly reduces environmental impacts through a zero-burden approach. Furthermore, it is important to note that plastic pallets generally exhibit higher impacts in several other categories, including carcinogenic effects, fossil fuel depletion, acidification, and eutrophication. Deviatkin et al. (2019) further report from the study of Kurisunkal (2010) that the only category in which plastic pallets show better performance compared to wood pallets is land use.

#### 3.4.2.5 Wood-plastic Composites

Furthermore, wood plastic composites show better performance in comparison to fossil-based plastics in impact categories of GWP and NREU., including biogenic carbon credits for biocomposites in the cradle-to-gate system boundary (Zuiderveen et al. 2023). Weiss et al. (2012) also reported that bio-composites, however unknown whether wood-based or natural fibre-reinforced plastic composites, show better performance in terms of climate change, NREU, eutrophication, acidification, and tropospheric ozone depletion, except trade-offs in stratospheric ozone depletion.

#### 3.4.2.6 Emerging Products

Besides traditional wood-based products, there are also emerging products manufactured from woody biomass, i.e., biochemicals and textiles. Biochemicals from woody biomass are already discussed in the biochemicals section 3.3.2. Regarding textiles, metanalysis by Zuiderveen et al. (2023) reveals that nanocellulose (micro fibrillated cellulose) derived from wood pulp has lower GWP (excluding biogenic carbon) as compared to fossil counterparts (carbon nanofibers).

### 3.4.3 Circular Economy

To address the circular economy perspective of the wood based products, this section highlights EoL management of wood-based products in the EU. Further, this section reflects on the cascade use and the core circular economy principles of wood based products. It integrates evidence from recent LCA reviews and EU data sources to show how current EoL practices align with or diverge from circularity goals. It further highlights the EoL treatment and use of wood waste in range of BBPs closing the materials use loop.

#### 3.4.3.1 EoL Options for Wood-based Products

A review by Costa et al. (2024) reports that for wood-based panels and LCA studies, different EoL options are considered, including reuse, recycling, recycling (cascading), incineration with energy recovery and landfill. Wood based products can be reused for the same purpose elsewhere or can be repurposed for other objects (Carvalho Araújo et al. 2019; Keene and Smyth 2009). However, The (Costa et al. 2024) reports that most studies considered incineration as the main EoL option, followed by landfill disposal and recycling for wood based panels. However, a landfill ban was issued in some countries, e.g. in Germany, where 84.7 % is accounted for by energy use and 15.3 % by material use (Mantau 2023). Incineration, although, is not a sustainable EoL option, as Werner and Richter (2007) reports that EoL incineration of wood-based products can cause higher impacts of acidification and eutrophication than other conventional products, although thermal energy can be recovered.

#### 3.4.3.2 Cascade Use and Resource Efficiency

The review by Costa et al. (2024) reports that some studies also included the cascading principle, which uses biomass residues and waste to extend the total biomass availability and to increase resource efficiency. Their review focused on LCA studies about producing particle board panels from woody biomass from different sources, including panels at EoL, because cascading systems are currently limited to particle board production (European Commission et al. 2016). Costa et al. (2024) report that wood cascading can reduce the consumption of virgin materials and is also more environmentally friendly, although it may lead to more requirements of materials and energy than the use of primary wood (Höglmeier et al. 2015; Rivela et al. 2006). A review by van den Auwelant et al. (2024) also reports the environmental benefits of cascading use. However, a review by Thonemann and Schumann (2018) concludes that the environmental performances of wood cascading are still not clear due to the variety of environmental impact categories and different system boundaries considered in the LCA studies.

However, cascading is also common in other woodworking sectors in the EU. The study by the European Commission et al. (2016) reveals that cascading materials are provided and utilised in almost all woodworking sectors, i.e., sawmill industry, panel industry, pulp industry, and wood plastic composites. A cascading EoL approach is a key solution to mitigate the impacts of climate change (van den Auwelant et al. 2024). The highest provision and utilisation sector of cascading materials by quantity in the finished product industry is the paper industry, followed by furniture and construction in utilisation rate (European Commission et al. 2016).

#### 3.4.3.3 Circular Stretegies in Woodworking sector

A review by van den Auwelant et al. (2024) determines the circular strategies in the woodworking sector and highlights the key lessons learned. The study reports narrowing the loop by using fewer resources, maximising efficiency, and minimising waste. Then, slowing the loop that focuses on extending the lifespan of wood-based products, encouraging durability, reuse and reparability. This is followed by closing the loop, which involves promoting recycling, remanufacturing, downcycling, and upcycling to minimise reintegrating the products into the production cycle rather than being discarded. Lastly, regenerating nature prioritises the use of non-toxic materials, adopting renewable energy sources, and restoring ecosystems affected by wood extraction and production. These strategies collectively contribute to a more sustainable and circular woodworking industry.

#### 3.4.3.4 Quantitative Evidence of Circular Flows

Overall, wood, paper, and cardboard make up 45% of the total biogenic waste generated in the EU (the year 2020), coming from the different economic sectors where the manufacturing sector produces the highest waste (Fernández Ocamica et al. 2024). According to the wood resource balance of the EU for the year 2017 (Cazzaniga N.E et al. 2021), 27% of the total wood supply comes from secondary resources (i.e., industrial residues), while 5% of the total supply comes from post-consumer wood waste. The utilization of by-products (black liquor, sawmill residues, wood chips, and particles), between the years 2009 and 2017, were dedicated 40% for material purposes, whereas the remaining 60% were allocated to energy uses (Avitabile et al. 2023).

According to the EoL biogenic waste treatment data (2022) (EUROSTAT 2025), wood waste were consumed 51% for energy (R1) purposes. While the materials and other recovery (R2-R11) amounted to 48% with a minor share (1%) of disposal-landfill and incineration. Paper and cardboard wastes, however almost entirely (98%) used for recovery- recycling and backfilling (R2-R11), with 1% for energy use. Regarding the potential of biogenic waste that can serve as a biomass feedstocks for range of BBPs, wood waste has significant role. For example, an extensive review by Fernández Ocamica et al. (2024) reveals that biogenic wood waste can be used in the textiles, wood products, paper and biochemicals beside being used in energy sector. This shows significant importance of wood waste in promoting the EU circular bioeconomy.

### 3.4.4 Hotspots Analysis

Energy consumption emerges as the main hotspot in the production and processing of wood products. For example, particle board or fibreboard, although it makes more efficient use of the wood of a tree compared to solid wood products, there is a high consumption of fossil energy associated with the production of fibres and particles/chips as well as with the production of glues, resins, etc. (Werner and Richter 2007). This increases the impacts associated with fibre board and particle board higher. Similarly, a review by Deviatkin et al. (2019), while comparing plastics and wood pallets, reveals that generally wood-based pallets are more environmentally friendly, and the reason is that plastic pallets require a high amount of energy compared to wood-based pallets. Furthermore, while there are resource efficiency and environmental benefits of cascading use of wood systems, as reported by (Costa et al. 2024), the high energy use can limit the environmental benefits (Rivela et al. 2006). A review by Füchsl et al. (2022) reveals that energy is needed during the production process, and also, the bonders and additives are the main hotspots in wood fibre insulation material boards.

### 3.4.5 Environmental Performance Matrix

A first comparative analysis on wood-based products with reliable results can be found in the review by (Werner and Richter 2007). The study by Deviatkin et al. (2019) focused specifically on pallets. Additionally, a meta-analysis by Zuiderveen et al. (2023) reports data on wood-plastic composites, while Weiss et al. (2012) offers information on floorboarding and composites. However, since it is unclear whether the composites discussed in (Weiss et al. 2012) study are wood-plastic composites, only the floorboarding information is considered from that study. van den Auwelant et al. (2024) reviewed environmental impacts of biobased building and construction materials in comparison to other materials. Cosentino et al. (2023)

and Füchsl et al. (2022) reviewed the environmental impacts of biobased insulation materials (including wood fibre insulation board and cellulose).

Based on the information of these review and meta studies, we developed an environmental sustainability matrix to assess the common environmental benefits and trade-offs highlighted (Table 3-5). The findings indicate that wood-based products offer significant environmental benefits in areas such as climate change mitigation, eutrophication, acidification, and non-renewable energy consumption. However, it remains challenging to quantitatively report these environmental benefits due to the diverse methodologies and uncertainties. However, this work provides a valuable qualitative assessment of wood-based products in comparison to conventional alternatives**.**

*Table 3-5: Environmental sustainability matrix for assessing wood-based products in comparison to products from other materials, The green box means the study found biobased polymers have fewer impacts, the red box represents higher impacts related to fossil-based plastics, and the grey box represents that the impact category is not explicitly mentioned or unclear (GWP; Global warming potential, EP; Eutrophication potential, AP; Acidification potential; NREU; Non-renewable energy use, AD; abiotic depletion; LU; Land use; WU; Water use, PM; particulate matter; TOF; Terrestrial ozone formation; POF; Photochemical ozone formation; SOD; Stratospheric ozone depletion, HTP; Human toxicity potential.*

| Source | GWP | EP | AP | NREU | AD | LU | WU | PM | TOF | POF | SOD | HTP |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (Werner and Richter 2007) | 🟩 | 🟩 | 🟩 | 🟩 | ▨ | ▨ | ▨ | ▨ | ▨ | 🟩 | 🟩 | 🟩 |
| (Deviatkin et al. 2019) | 🟩 | 🟩 | 🟩 | 🟩 | ▨ | 🟥 | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ |
| (Zuiderveen et al. 2023) | 🟩 | ▨ | ▨ | 🟩 | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ |
| (Weiss et al. 2012) | 🟩 | 🟩 | 🟩 | 🟩 | ▨ | ▨ | ▨ | ▨ | 🟥 | ▨ | ▨ | ▨ |
| (van den Auwelant et al. 2024) | 🟩 | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ |
| (Cosentino et al. 2023) | 🟩 | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ |
| (Füchsl et al. 2022) | 🟩 | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ |
| Overall impacts | 🟩 | 🟩 | 🟩 | 🟩 | ▨ | 🟥 | ▨ | ▨ | ▨ | 🟩 | 🟩 | 🟩 |

### 3.4.6 Uncertainty Factors and Recommendations

When analysing the environmental impacts of wood-based products, it is challenging to make sustainability claims due to various uncertainty factors. Review and meta-analysis studies identified significant variations in impacts arising from different methodological assumptions and considerations that further complicate drawing clear conclusions. These uncertainty factors include different LCA methodological differences, i.e., differences in system boundaries, functional unit and allocation method. Furthermore, differences in biogenic carbon accounting methods and lack of harmonization in this regard also lead to complexity in sustainability assessment. Similarly, LCA modelling assumptions and diverse impact assessment methods further complicate this process.

To ensure a more robust and accurate sustainability assessment of wood-based products, harmonization of LCA methodologies and standardized guidelines for proper documentation of the LCA studies and reliable life cycle inventories are essential. LCA should be integrated at the early stages of product development, incorporating technological innovations and regional and temporal aspects in databases. A cradle-to-grave system boundary and harmonized impact assessment methods should be used, including land use assessments and integration with forest ecosystem services such as biodiversity and landscape evaluation. Given the complexity of the wood product sector, multiple environmental impact categories should be considered, and sensitivity analyses should be performed to interpret results accurately. Additionally, multicriteria decision making should be applied to balance conflicting criteria across LCA, SLCA, LCC, and LCSA, ensuring a comprehensive, multidimensional sustainability evaluation of wood-based products. To further improve the environmental profile of wood-based products, EoL considerations should follow a cascading approach, optimizing material reuse and minimizing waste.

#### 3.4.7 Critical Aspects

There are many critical aspects identified in the studies that lead to uncertainties; this includes methodological differences, allocation methods, assumptions related to end-of-life scenarios (Werner and Richter 2007; van den Auwelant et al. 2024).

##### 3.4.7.1 Biogenic Carbon Accounting and GWP Reporting

A central issue remains regarding accounting for the various types of global warming potential (GWP fossil, GWP biogenic, GWP LULUCF) as requested e.g. in the standard (EN 15804 2022) for the building products used in the construction sector, while comparing wood-based and other materials. Another issue is the biogenic carbon accounting while comparing wood based products to fossil based products. As already stated by Werner and Richter (2007), also in up-to-date LCA studies, the biogenic carbon accounting is not reported from the reviewed studies. The review by Deviatkin et al. (2019), does not report clearly the biogenic carbon accounting used in all reviewed studies, while comparing wood-based and plastic pallets. Similarly, a review by (Costa et al. 2024), analysing wood-based panels LCA studies, reveals that most studies do not report data on biogenic $CO_2$ flows. Some studies considered biogenic carbon neutrality which means that the $CO_2$ removal by wood production in the forest is equal to the $CO_2$ emission at the end of the life cycle of wood-based panels due to the inherent material characteristic of wood, but other studies used different approaches. Some studies used carbon storage in wood-based panels as a credit to offset the fossil-based emissions, which is not scientific valid. At the same time, some considered the delayed emissions due to temporary or permanent carbon storage. Such different use of biogenic carbon accounting leads to significant variations in results (Costa et al. 2024). However, the 0/0 approach (also called carbon neutral approach (Lesly Garcia-Chavez et al. 2023)) for biogenic carbon accounting is an oversimplified approach, that assumes all materials are incinerated at EoL, and it lacks incentive for the reuse, recycling or the prolonged service life of BBPs (Bio-Based Industries Consortium 2025). Instead, Bio-Based Industries Consortium (2025) proposes to use -1/+1 approach when comparing BBPs with fossil-based products, which is also stated by the (EN 15804 2022). Furthermore, Lesly Garcia-Chavez et al. (2023) reviewed the standards and guidelines to report on biogenic carbon accounting method, and revealed that most standards and guidelines (i.e., ISO 14067, PAS 2050, GHG Protocol, ILCD Handbook, ISO 21930 and EN 15804) explicitly or implicitly consider -1/+1 approach by tracking all biogenic carbon flows. This approach will ensure a more fair, transparent, and intuitive comparison, allowing decision-makers to choose based on the climate benefits of BBPs (Bio-Based Industries Consortium 2025; Lesly Garcia-Chavez et al. 2023). Additionally, changes of biogenic carbon sequestration in the forest overtime due to forest management issues or natural disturbances and the long-term carbon storage associated with the utilization and lifetime of wood products has to be considered. As van den Auwelant et al. (2024) report that temporary carbon storage is acknowledged by standards as a crucial factor to be considered in LCA of wood-based products. By overlooking biogenic carbon, we risk producing misleading comparisons. It is important to recognize that a significant advantage of bio-based products over fossil-based alternatives lies in their capacity for carbon sequestration and the delayed emissions. For example, study by Hill et al. (2018) reveals that when biogenic carbon is included for cellulose based insulation materials the GWP further decreases, as compared to when biogenic carbon is excluded. Thus, the potential carbon storage effects of the forests and wood products as well as the potential substitution effects have to analysed taking time and space into account.

# 4 Conclusions

This review underscores the opportunity presented by IBBS to mitigate climate change impacts, diversify resource inputs, and contribute to a more circular bioeconomy. Bioplastics can significantly reduce climate change impacts and non-renewable energy use compared to fossil-based plastics. Yet, they may have potential burdens such as increased acidification, eutrophication, water consumption and land use due to increased fertilizers, pesticides and other agricultural practices associated impacts. Similarly, biochemicals hold promise in climate change mitigation and non-renewable energy use, but robust data are often lacking, and diverse feedstocks complicate standardized assessments and make concrete conclusions for the potential trade-offs. Traditional wood-based products show advantages in many environmental categories, particularly in reducing climate change impacts, non-renewable energy use, and even eutrophication and acidification impacts.

In general, the impacts significantly change due to cascading practices, biogenic carbon accounting and potential waste management practices at their end of life. Nonetheless, key challenges persist because most BBPs still have low TRL. These emerging products require novel processing routes, technological innovation in processing, and more sustainable end-of-life waste management. In addition, inconsistencies in methodological choices, such as system boundaries, functional units, impact assessment methods, and carbon accounting, have led to large uncertainties, making it difficult to conclude on the net environmental benefits of BBPs.

This work determines the need for more extensive review and metanalysis studies based on harmonized methodological frameworks, refining system boundaries and functional units, and carefully managing biogenic carbon flows, which are all important to producing reliable results and providing more evidence for decision-making. The greatest improvements will likely come from integrating novel feedstocks and sustainable agricultural and forestry practices, using integrated biorefinery and cascading systems concepts, improving the efficiency of conversion processes, energy efficiency and greener electricity mix and selecting the most appropriate EoL waste management, i.e., recycling to further promote the sustainable and circular bioeconomy. Additionally, the pressure of climate change on the agriculture and forest ecosystems with possible reduced growth due to disturbances by drought, storms, insects, etc. and their development for climate adapted, stabile stands have to taken into account for prospective scenarios and analyses. Therefore, policymakers, industry stakeholders, and researchers must collaborate to embed lifecycle thinking, standardization, and transparent reporting into future BBPs development. In the end, the success of IBBS relies on achieving complete sustainability by balancing environmental, social, and economic factors that will lead us toward a truly sustainable circular bioeconomy of BBPs in the EU.

*Table 4-1: A review and meta-studies were analysed in this study for environmental and circularity assessment of biobased products.*

| **Source** | **Goal of the study** | **Methodological considerations/Assumptions** | **System boundary** | **Unit** | **Environmental benefits** | **Trade-offs** | **Geography** |
|---|---|---|---|---|---|---|---|
| (Ali et al. 2023) | Impacts fossils vs biobased-based plastics, LCA challenges, EoL strategies | Review of LCA studies (economic/social aspects) | Cradle to the grave (sometimes not specified) | Declared unit (Kg) | Fossil resources, NREU, carbon footprint | Eutrophication, land consumption | Mixed |
| (Gerassimidou et al. 2021) | Trade-offs of biopolymers, Sustainability matrix | Review of LCA studies over the entire life cycle, 1st generation feedstock bioplastics | Cradle to grave | Declared unit | - | Eutrophication, acidification, land use change, and ecosystem quality degradation (includes water consumption, ozone depletion, photochemical ozone formation, ecotoxicity). | Mixed mostly EU |
| (Brizga et al. 2020) | Environmental consequences of biobased plastics | Data from the LCA studies is taken irrespective of their consideration regarding system boundary, FU, allocation procedure, etc. | Mixed | Declared unit (kg) | GWP | land use, water use | Mixed |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| (Weiss et al. 2012) | Environmental impacts of biobased materials (biopolymers) | Data were taken from LCA studies irrespective of consideration for system boundaries, functional units, life cycle scenarios, and allocation methods. | Mixed | Declared unit (per metric ton of product, per hectare of agriculture land and year (ha*a) | NREU, climate change, tropospheric ozone depletion | Eutrophication, stratospheric ozone depletion | Mixed |
| (Zuiderveen et al. 2023) | Impacts bio-based vs fossil counterparts (Biopolymers) | Analysis of pLCA studies by comparing the emerging products with the fossil-based counterparts. In EoL, only incineration is used, biogenic carbon emissions are considered as CO2 neutral | Cradle to grave | Declared unit (Kg) | GHGs, NREU, human toxicity, marine aquatic toxicity, terrestrial ecotoxicity | eutrophication, acidification, ozone depletion, and photochemical ozone formation; freshwater ecotoxicity, land use, water scarcity, depletion of abiotic resources | Mixed |
| (European Commission 2019) | Impacts bio- vs fossil- based polymers | Industrial data for biobased products, literature data is used for fossil based products, biogenic carbon neutrality, marginal mixes substitution | Cradle to grave | FU | climate change, abiotic depletion | particulate matter, terrestrial ozone formation, photochemical ozone formation | EU mostly |
| (Weiss et al. 2012) | Environmental impacts of biobased | Data taken from LCA studies irrespective of consideration for system boundaries, functional | Mixed | Declared Unit | Climate change, NREU | Eutrophication, Stratospheric ozone depletion | Mixed |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | materials (biochemicals) | units, life cycle scenarios, and allocation methods. | | | | | |
| (Rinke Dias de Souza et al. 2024) | Opportunities and challenges of biochemicals | Literature review | Mixed | - | GHGs | - | - |
| (Zuiderveen et al. 2023) | Environmental impacts biobased vs fossil based products (biochemicals) | Analysis of pLCA studies by comparing the emerging product with fossil counterpart, In EoL only incineration is used, biogenic carbon emissions considered as CO2 neutral | Cradle to grave | Declared unit (kg) | GWP, NREU | Acidification, Eutrophication, ozone depletion, photochemical ozone formation | Mixed |
| (Ögmundarson et al. 2020a) | comparing of biobased chemicals to fossil chemicals that are functionally equal | Only commercialized biobased chemicals, | cradle to grave | Declared unit | GWP, NREU, abiotic resource use, particulate matter formation | Land use, eutrophication, water use, acidification | Mixed |
| (Eisen et al. 2020) | compare biobased and fossil-based adhesives | Systematic literature review | Mixed | Mixed | GWP, human | - | Mixed |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | | toxicity potential | | |
| (Ioannidou et al. 2020) | availability of side streams of industrial and food supply chain to be used for biochemical production | Literature review | - | declared | - | - | - |
| (Fiorentino et al. 2017) | technological and environment comparison of biobased vs fossil-based chemicals | Literature review | Mixed | - | GHGs, fossil fuel use (abiotic depletion (fossil fuels), NREU, human toxicity potential, fossil depletion potential, metal depletion potential | land use, water use, photochemical oxidant formation potential, terrestrial ecotoxicity potential | Mixed |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| (Werner and Richter 2007) | comparison LCA of wood-based building material to functionally equal conventional products (mean value) | only functionally equivalent, and no methodological flaws were included in the assessment | Cradle to the grave (mostly) | FU | GHGs, consumption of non-renewable energy and cumulative energy demand, | higher consumption of renewable energy carriers | Mostly EU |
| (Deviatkin et al. 2019) | compare the LCA of wood and plastic pallets | Literature review | Cradle to grave | Mixed | Climate change | Land use | Mixed |
| (Costa et al. 2024) | impact of wood panels from LCA perspective, mythological choices and challenges | Literature review | Cradle to gate | Declared unit (m3) | - | - | Mixed |
| (Weiss et al. 2012) | Environmental impacts of biobased materials (floorboard) | Data taken from LCA studies irrespective of consideration for system boundaries, functional units, life cycle scenarios, and allocation methods. | Mixed | Declared unit | Climate change, NREU, eutrophication, acidification | tropospheric ozone depletion | Mixed |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| (Zuiderveen et al. 2023) | Environmental impacts biobased vs fossil based products (wood plastic composites) | analysis of pLCA studies by comparing emerging product with fossil-based counterpart, | Cradle to gate | Declared unit | GWP, NREU | - | USA |
| (van den Auwelant et al. 2024) | Perspective on LCA in wood working sector and suggestion to reduce environmental impacts | Systematic literature review | Mixed | Mixed | GWP | - | Mixed |
| (Cosentino et al. 2023) | Environmental impacts of biobased and conventional insulation materials | Systematic literature review (wood-based insulation materials include biogenic carbon) | Mixed | FU | GWP | Total primary energy use | Mixed |
| (Füchsl et al. 2022) | Environmental impacts of biobased and conventional insulation materials | Literature review | Cradle to gate | FU | GWP, CED | - | Mixed |

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