HEMI-COAT

Conversion of hemicellulose to coatings

36th CORNET call

D1.5
Life Cycle Assessment on the production of Itaconic Acid

cornet Collective Research Networking

INDUSTRIELLE GEMEINSCHAFTSFORSCHUNG IGF

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Disclaimer

This deliverable has been prepared in the context of the funded project HemiCoat in the framework of the Collective Research Networking (Cornet) supported by the Federal Ministry for Economic Affairs and Climate Action (BMWK, funding code 01IF00399C) through the AiF (German Federation of Industrial Research Associations e.V.) based on a decision taken by the German Bundestag and by the Walloon region as funding with the n° 2310168 (Convention number).

The views expressed in this HemiCoat Deliverable *D1.5 Life Cycle Assessment on the production of Itaconic Acid*, which evaluates the environmental impact of Itaconic acid from the raw material, which is a xylose-enriched woody hydrolysate based on an extraction process of OÜ Fibenol, through the production of Itaconic acid simulated at an industrial scale, are the sole responsibility of the author and do not necessarily reflect the views of the industries of the User Committee. The User Committee is not responsible for any use that may be made of the information contained therein. The author does not accept any liability for any direct or indirect damage resulting from the use of this Deliverable to its content or parts of it. The results achieved, conclusions made, and recommendations given by the author should not be interpreted as a political or legal signal that the European Commission or any other political or legal institution intends to take a given action.

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Abbreviations

Abbreviation	Description
EF	Environmental Footprint (Life Cycle Impact Assessment Methodology)
FU	Functional Unit
HC	Hemicellulose
IA	Itaconic acid
IPPC	The Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
PIA	Polyitaconic acid
SDS	Sodium dodecyl sulfate
SME(s)	Small and medium-sized enterprise(s)
UC	User Committee
WP	Work package
Unit abbreviation	
CTU_e	Comparative Toxic Unit for the ecosystem
CTU_h	Comparative Toxic Unit for human
kBq U^{235}	kilobecquerel of $Uranium^{235}$
kg CFC-11 eq	kilogram of CFC-11 (Trichlorofluoromethane) equivalent
kg CO_2 eq	kilogram of carbon dioxide equivalent
kg N eq	kilogram of nitrogen equivalent
kg NMVOC eq	kilogram of non-methane volatile organic compounds equivalent
kg P eq	kilogram of phosphor equivalent
mol H^+ eq	mole of hydrogen ion equivalent
mol N eq	mole of nitrogen equivalent
kg world eq. deprived	equivalent kilogram of an average global resource made unavailable
kg Sb eq	kilogram of antimony equivalent

1. Executive summary

Deliverable *D1.5 Life Cycle Assessment on the production of Itaconic Acid* is the relevant framework to estimate, evaluate, and communicate selected environmental impacts of Itaconic Acid production alongside the HemiCoat cascade simulated at an industrial scale, to evaluate sustainability claims, regulatory compliance, procurement decisions, and comparisons between alternative production pathways. Therefore, this report is essential to Work package *WP 1 Biomass Potential & Life Cycle Assessment*, which is under the responsibility of DECHEMA e.V. and DBFZ gGmbH. The present deliverable is based on exchanges during the HemiCoat meetings within the duration of the project in exchange with the enterprises representing the User Committee, as well as the consortium's monthly online meetings. This consortium consists of the following partners: DECHEMA e.V., DBFZ gGmbH in Germany, Celabor s.r.l., Materia Nova in the Walloon region.

2. Introduction

HemiCoat's overall project objective is to valorize hemicellulose (HC) by-products from paper pulp manufacturing and agricultural lignocellulosic biomass to obtain added-value products. Herein, the project represents the idea of utilizing all components of natural commodities, specifically of wood, to maximize resource efficiency, reduce waste, and improve the sustainability of biomass utilization. Woody biomass offers unique properties that can be valorized into high-value products, contributing to a circular (bio-)economy. This holistic approach can minimize environmental impact, lower fossil resource dependency, and enhance the economic viability of wood-processing industries. However, HC, a significant fraction of the woody biomass, remains largely underutilized despite its potential to produce bio-based, sustainable alternatives to fossil-derived products. It is used mainly to recover energy through burning. Simultaneously, the coatings and adhesives industries are facing increasing demand for bio-based, low-carbon products that reduce reliance on fossil resources, align with regulatory changes, and eliminate hazardous compounds.

The HemiCoat (Hemicellulose to coatings) project aims to valorize HC streams, particularly HC breakdown products obtained from isolation processes for cellulose and lignin, to produce added-value chemicals for coatings, adhesives, and functional additives. HC monomeric pentoses are fermented into itaconic acid (IA), which undergoes further chemical modifications. In a parallel approach, HC oligomers are transformed chemically into sustainable wood adhesives. **Figure 1** shows an overview of the HemiCoat processes.

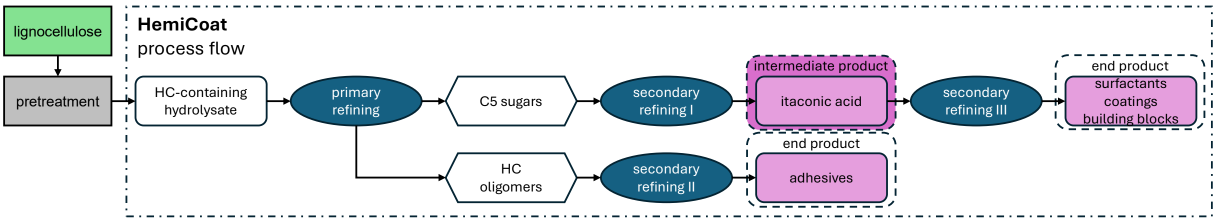

Figure 1. Overview of the HemiCoat process flows.
HC breakdown products from differently pretreated wood hydrolysates are separated in a primary refining process to obtain a C5 sugar (pentose) fraction, mainly xylose, and HC oligomers. In secondary refining, the xylose is fermented to IA, the key intermediate product chemically modified in a secondary refining III to produce surfactants or coatings, the end products of the HemiCoat process flow. In a parallel process, HC oligomers, after primary refining, are transformed into adhesives in secondary refining II. The resulting adhesives are the second line of end products of the HemiCoat process.

To investigate the potential environmental performance of the process developed within the HemiCoat project for the production of IA, an attributional LCA was performed. The assessment characterizes the environmental impacts associated with the process chain up to the production and purification of IA and provides a basis for evaluating the potential sustainability benefits or weak points of the developed process. The results are interpreted in relation to suitable production routes for IA from literature. Therefore, this report defines the methodological framework, system boundaries, settings, and assumptions required to assess the environmental performance of the process at the selected product-system level based on the HemiCoat cascade.

The results of this LCA are compared with the environmental impact of the production of IA reported in literature, e.g., produced from wheat straw.[1]

This report presents an LCA of the HemiCoat project process chain up to the production and purification of IA, based on the process definition and data provided by the technical-economic evaluation (TEA) and comprehensively assesses the environmental performance of these innovative processes while identifying potential trade-offs and areas for improvement. Further chemical conversion routes and the utilization of the oligosaccharide side stream are excluded because no corresponding TEA-based process data are available, and relying solely on laboratory-scale data would not provide a sufficiently robust basis for a representative LCA.

2.1. Mapping HemiCoat's outputs

This section aims to map HemiCoat's grant agreement commitments within the formal deliverables and task descriptions against the project's respective outputs and work performed. This report is listed as Deliverable *D1.5* and is due in M24 of the project, August 2026. Together with its preparatory work *D1.4 Interim report on definitions, settings and system for LCA*, which was due in M9, June 2025, both deliverables are assembled in *WP 1*, *task 1.4 Life Cycle Assessment*. **Table 1** lists, describes, and justifies the tasks and subtasks in HemiCoat connected to *task 1.4*.

Table 1. Adherence to HemiCoat's task 1.4 description & Deliverables.

HemiCoat task	Description	Justification
Task 1.4 Life Cycle Assessment (M4 to M24)	Results from experimental work, feedstock potential analysis, and market analysis will be used to conduct an LCA of the entire process chain, which leads to *D1.5 LCA of hemi-cellulose oligomers and itaconic acid-based products*.	Evaluation of the environmental impacts of products and processes across the HemiCoat production chain, enabling sustainability improvements
Subtask 1.4.1 Definitions and settings	Identification of crucial parameters of the LCA as part of *D1.4*	Provides the basis for task 1.4 in *WP 1*, allows for consistent results, and enables appropriate data collection for the other tasks involved in *WP 1*
Subtask 1.4.2 Qualitative system description	Definition of the system boundaries, key processes, and interactions within the product life cycle without using quantitative data, providing an overview of inputs, outputs, and environmental considerations as part of *D1.4*	
Subtask 1.4.3 Goal and scope definition	Defines the purpose of the LCA, the intended application and audience, the functional unit, system boundaries, allocation procedures, assumptions, and limitations as part of *D1.4* revisited in *D1.5*	Establishes the framework of the study and ensures that the assessment addresses a clearly defined question with transparent and consistent boundaries
Subtask 1.4.4 Life Cycle Inventory (LCI)	Collects and quantifies all relevant inputs and outputs of the product system, including raw materials, energy, water, emissions, products, co-products, and waste in *D1.5*	Provides the primary data basis for calculating the environmental performance of the system and ensures that material and energy flows are accounted for
Subtask 1.4.5 Life Cycle Impact	Converts the inventory flows into potential environmental impacts using appropriate impact categories and characterization	Makes it possible to interpret the significance of the inventory data and compare the environmental

[1] Rebolledo-Leiva et al., "Environmental Assessment of the Production of Itaconic Acid from Wheat Straw under a Biorefinery Approach."

Assessment (LCIA)	methods, such as climate change, acidification, eutrophication, and resource use in *D1.5*	relevance of different life-cycle flows
Subtask 1.4.6 Interpretation	Evaluates the LCA results, identifies environmental hotspots, examines sensitivity and uncertainty, and derives conclusions and recommendations in *D1.5*	Ensures that the results are critically assessed, scientifically meaningful, and useful for decision-making and process improvement
Subtask 1.4.7 Reporting and critical review	Documents the methods, data, assumptions, results, limitations, and conclusions; where required, the study is reviewed internally or by an independent third party in *D 1.5*	Promotes transparency, credibility, reproducibility, and compliance with applicable LCA standards, particularly when results are used for external comparison or public claims
HemiCoat Deliverables		
D1.4 Interim report on definitions, settings, and system for LCA. The report defines the initial methodological framework for the HemiCoat LCA in *D1.5*.		
D1.5 Life Cycle Assessment on the production of Itaconic Acid. Previously named as *D1.5 LCA of hemicellulose oligomers and itaconic acid-based products*.		

The HemiCoat LCA interim report *D1.4*, defining and setting up the LCA system, paved the way for the attributional LCA documented in this report. Herein, the environmental impact of utilizing HC streams in the scope of the project is quantified, offering an understanding of whether bio-based products from HC side streams may contribute to sustainability goals. An economic analysis of the HemiCoat process cascade was performed in Deliverable *D1.6 HemiCoat market analysis and exploitation strategy* and thus is excluded from this report. However, ecological and economic analyses are combined and form the sustainability assessment in HemiCoat in the final report of the project.

2.2. Sustainability assessment in HemiCoat

The sustainability assessment within HemiCoat is integrated in the work package 1 (*WP 1 Biomass potential & Life Cycle Analysis*), whose main objectives include:

- The assessment and improvement of the sustainability impacts of the HemiCoat processes leading to Itaconic acid as the intermediate product of the project by providing objective information regarding key sustainability aspects using scientific, transparent, and reproducible methodologies.
- The assessment of the sustainability and techno-economic feasibility of the HemiCoat processes and products, along with their production in a comprehensive manner. Herein, the process assessment will be based on the TEA simulation in *D1.3 Internal report on mass and energy balance of the process* obtained from the technical results of *WP 2* and *WP 3* and, if required, supplemented by literature.
- The provision of iterative feedback to the process developers as part of *WP 2* and *WP 3* to further optimize the processes in the form of estimation and up-scaling of woody biomass & hydrolysate potential from industry, and an ecological assessment (LCA), as well as an economic evaluation of the HemiCoat intermediate product Itaconic Acid.

The main objective of *WP 1* is to assess the sustainability of the HemiCoat value chains comprehensively, covering two key aspects of sustainability: environment and economy. **Figure 2** maps *D1.5 Life Cycle Assessment on the production of Itaconic Acid* within the

Sustainability Assessment in *WP 1* and interconnects the *WPs* (see section *2.1 Mapping HemiCoat's outputs*).

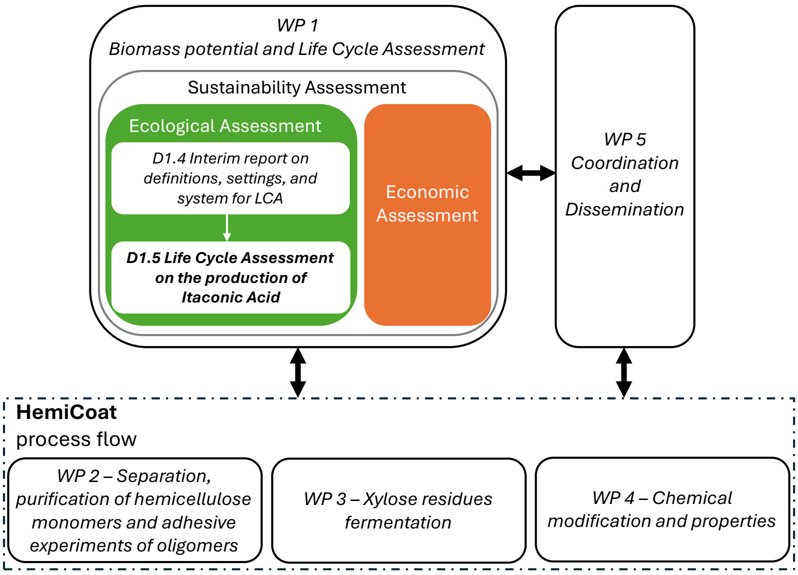

Figure 2. Work packages in HemiCoat and mapping of the present report D1.5 within the sustainability assessment.

The social dimension is excluded from the investigation since it is not among the main drivers of sustainability in this context, being considered indirectly through existing corporate policies. The comparable small relevance of social aspects in the HemiCoat concept can be explained in the following:

- Well-established regulatory and social standards exist in Central and Western European industries, such as Germany and Belgium, the regions of the project, due to strict labor laws, workplace safety regulations, and social responsibility requirements enforced by the EU and national governments.
- The overall minimal direct social impact in highly automated processes in industries connected to the HemiCoat processes, which often rely on specialized labor (and automatization), and thus fewer human workers are directly affected by daily operations.

On the other hand, economic and environmental aspects, with their quantifiable metrics e.g., CO_2 equivalent emissions, resource use, economic growth, etc. are prioritized in HemiCoat's sustainability assessment, since both, economic viability and environmental compliance, are required in the competitive industrial sectors connected to HemiCoat (e.g. manufacturing of chemicals and chemical products, reclaimed wood processing, and others) to remain the competitiveness in the European and global market.

The sustainability assessment will reveal the advantages, disadvantages, and trade-offs in the HemiCoat value chains compared to established routes. The HemiCoat value chains are the sequential workflow from the production of the HC hydrolysates to the desired final products and product classes of the project:

1. Separation and purification of HC monomers and adhesive experiments of oligomers (WP 2)
2. Xylose residues fermentation to IA (WP 3)
3. Chemical modification and properties (WP 4), excluded from *D1.5*, but included in *D1.6*

For reliable and robust sustainability assessment results, the principles of comprehensiveness during the life cycle stages of products must be considered. A systematic overview will allow to identify and possibly minimize the unintentional shifting of environmental burden and economic benefits between life cycle stages or individual processes. The production of IA, the key intermediate product of the HemiCoat process flow, will be compared to alternative production route(s) from literature, e.g., from wheat straw under a biorefinery approach.[2] However, the sustainability performance of HemiCoat end product production(s), e.g., polyitaconic acid (PIA) will not be evaluated in view of the lack of available results from the technical-economic assessment.

The sustainability assessment in HemiCoat evaluates the feasibility to minimize selected environmental impacts, such as emissions or energy demands, compared to a benchmark while maintaining competitive production costs in a commercial-scale setup. This is accomplished by translating experimental data from other project WPs through the TEA and implementing them into life cycle assessment models. The final integrated assessment(s) will utilize a multi-criteria evaluation software tool (openLCA), allowing to identify potential optimization pathways for the production of IA through the HemiCoat cascade.

2 Rebolledo-Leiva et al., "Environmental Assessment of the Production of Itaconic Acid from Wheat Straw under a Biorefinery Approach."

3. Definitions and settings for the ecological sustainability assessment

The (ecological) sustainability assessment requires common definitions and settings on which the environmental (and economic) evaluation will be based to ensure consistent data and results.

3.1. The HemiCoat biorefining concept

The HemiCoat project aims to valorize hemicellulose (HC) breakdown products from isolation processes for cellulose and lignin to obtain high value-added chemicals toward sustainable coatings, adhesives, and functionalized additives. The overall goals of the project are:

- Recovery of most of the HC oligomers from lignocellulose biomass processing
- Feasibility tests of the manufacturing of adhesives from the HC oligomers
- Use of the monomeric sugars and other residual compounds in a fermentative step to produce IA
- Usage of IA as a building block for chemical synthesis of surfactants and coatings

The overall concept of the HemiCoat biorefining project can be summarized in a primary refining and three secondary refining steps. In the primary refining, HC oligomers and C5 sugars are recovered and purified from wood-born hydrolysates. In the secondary refining step I, the concentrated and purified monomeric C5 sugars are fermented in a fed-batch process to IA. In parallel, in the secondary refining step II, the hydrolysate-born hemicellulosic oligomers are applied in formulations with chitin/chitosan as wood adhesives. Finally, in a secondary refining step III, the product of the secondary refining step I, IA, is purified for subsequent chemical modification to produce biobased products, e.g., surfactants or coatings. **Figure 3** shows the overall concept of the HemiCoat biorefining concept with the scope for this report highlighted in orange.

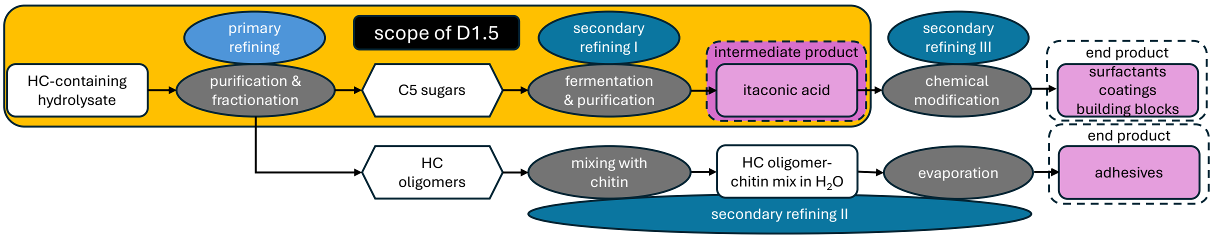

Figure 3. The HemiCoat refining concept.
The scope of this report *D1.5* is indicated by the orange background.

The overall goal of HemiCoat is to gain a sustainable and cost-effective purification and conversion of sugars from the HC fraction of lignocellulosic biomass to produce bio-renewable surfactants, coatings, and adhesives for applications. This can help SMEs that work with IA-based products by diversifying sources of supply, increasing quality, or decreasing costs. Moreover, HemiCoat may open the possibility of technological breakthroughs for related SMEs, such as the companies represented in the User Committee (UC) of the project, to replace their commonly used fossil-based reagents and materials with bio-based alternatives from IA and extend the field of application toward functionalized additives or coating materials. Likewise, the project can offer the potential to impact SMEs interested in the valorization of (their) lignocellulosic and hemicellulosic agro-industrial wastes and, therefore, can open new and sustainable business perspectives.

3.2. Goal and scope definitions and settings for the LCA

The goal and scope definition phase is a critical first step in an ISO-standardized LCA. In this phase, the purpose of the assessment is established, and key decisions are made regarding the details of the product system under study. According to ISO 14040[3] and 14044[4], this phase is more than just an introduction to the LCA process, but plays a fundamental role in shaping the entire LCA study. Before data collection begins, by defining the goal and scope at the outset, it can be ensured that the methodology is structured and aligned appropriately with the intended objectives, and the foundation for a robust and meaningful LCA is set.[5]

The initial planning phase of the (HemiCoat) LCA study involved defining key aspects such as the study's objective, target audience, and product characteristics – including function, functional unit, and reference flows. Additionally, it established essential scope elements, including system boundaries, cut-off criteria, regional coverage, and considerations for multifunctionality.

3.2.1. Goal of the LCA

HemiCoat's attributional LCA aims to identify the implications of project process flows, including optimizations for the processes based on the TEA simulation in *D1.3*.

The primary *aim of the study* is to provide decision support for two main applications:

- the development of sustainable products based on a resource-efficient concept
- an improved technology development in comparison to a non-optimized process flow (at laboratory scale) and to other approaches from literature

The *target audience* of the study is decision-makers in the following fields:

- Research: Academic and research institutions such as universities and research centers contribute expertise in biomass valorisation, LCA methodologies, process optimization, and material characterization
- Industry: SMEs (and large enterprises) being engaged in hemicellulose extraction and the utilization of IA (which, for instance, could be chemically modified to deliver formulation of bio-based coatings or surfactants)
- Policy, Regulatory and Certification Entities: Compliance with sustainability directives is governed by national and European regulatory bodies, ensuring alignment with environmental and industrial policies.
- General public.

For these key stakeholders and institutional involvement, the following *main guiding question* occurs in HemiCoat's sustainability assessment.

How far and under which conditions can woody hydrolysate (containing hemicellulosic sugars as byproducts from the production of cellulose or lignin products) be used according to the HemiCoat process flow and contribute to a sustainable supply of Itaconic acid?

It is the goal of this report as a part of the sustainability assessment report is to answer this question. The main guiding question leads to the following *sub-questions*:

[3] "ISO 14040:2006 Environmental Management — Life Cycle Assessment — Principles and Framework."
[4] "ISO 14044:2006 Environmental Management — Life Cycle Assessment — Requirements and Guidelines."
[5] Curran, "Overview of Goal and Scope Definition in Life Cycle Assessment."

1. How do the HemiCoat process flow cascades compare from a sustainability perspective to the conventional (or alternative) production of IA
2. How do specific results from environmental and economic perspectives differ?
3. Which unit processes determine the results most, and what are the optimization potentials?
4. What would the impact of possible economic transitions, e.g., towards renewable energy, be?
5. Which barriers (e.g., technological) and limitations (e.g., biomass availability) may hinder the industrial-scale implementation of the HemiCoat processes or require changes to the concept that affect sustainability?

3.2.2. Scope definition and system boundaries of the LCA

The scope of an (attributional) LCA study specifies the products and systems to be analyzed. It must be well-defined to ensure that the study's comprehensiveness, depth, and detail align with its stated goal(s) (see 3.2.1). The resulting definitions and parameters guide subsequent analyses, ensuring consistency across environmental assessments. Key scope parameters including system definitions, functions, and geographical considerations are outlined in the following sections.

The definition of the boundaries is required to outline the investigated product system and its overall function. The scope of the current LCA ends with the production and purification of IA simulated at an industrial scale. Further chemical conversion or downstream workflows in which IA is used as an intermediate are outside the scope of this assessment. Consequently, the LCA does not evaluate the environmental impacts of potential subsequent products or applications based on IA. In addition, the side stream of the project that utilizes an oligosaccharide-enriched fraction generated from previous process steps at the DBFZ is not implemented in the present LCA system. This side-stream route as well as further chemical modifications of IA are excluded because its subsequent processing and application are not covered by the technical-economic assessment (TEA) and cannot therefore be described with a sufficiently robust and consistent set of process data within the current study.

The selected system boundary is directly linked to the results and level of detail of the technical-economic evaluation. In the current project, the TEA was conducted up to the production and purification of IA. It therefore provides the necessary process definition, material and energy balances, equipment assumptions, production-scale considerations, and other techno-economic parameters only for this part of the process chain. Beyond the production of purified IA, no TEA-based process design is available for the further chemical workflows or for the utilization of the oligosaccharide side stream. The LCA system boundary has consequently been aligned with the point up to which the process has been defined and evaluated in a sufficiently integrated manner.

Aligning the LCA with the TEA is essential to ensure that the environmental assessment is based on a coherent and technically plausible process scenario, that represents an industrial scale level. A meaningful LCA requires a defined process configuration, representative input and output flows, assumptions concerning scale-up, energy and utility requirements, material consumption, equipment operation, yields, purification steps, waste streams, and the treatment of co-products or side streams. These parameters were established through the TEA performed by the DBFZ (*D1.3 Internal report on mass and energy balance of the process*) and are associated to the process design of the HemiCoat cascade represent the translation of the laboratory-scale results from the HemiCoat consortium into a production scenario that can be assessed in this LCA.

In the absence of TEA data beyond the production and purification of itaconic acid, an LCA of the subsequent chemical workflows or the oligosaccharide side-stream route would have to rely predominantly on laboratory-scale data and on unverified assumptions regarding industrial implementation. Such an assessment would not provide a sufficiently representative basis for estimating the environmental impacts of the intended process at a relevant production scale. Even though laboratory-scale data can be useful for identifying process hotspots and for screening individual operations to a certain extent, they generally do not allow to consider effects of scale-up, changes in process efficiency, industrial energy demand, solvent and reagent recovery, equipment requirements, purification performance, waste management, or the allocation and utilization of side streams. Extending the LCA beyond the TEA-defined system boundary under these conditions could therefore create a misleading impression of precision and could compromise the comparability and interpretation of the results. For this reason, the LCA presented in *D1.5* is limited to the process steps for which a TEA-supported process description is available. This approach avoids introducing unsupported assumptions and ensures that the environmental results remain traceable to the technical and economic assumptions of the project. The chosen boundary does not imply that the subsequent chemical workflows or the oligosaccharide side-stream route are environmentally insignificant. Rather, their assessment is deferred until the corresponding process designs, scale-up assumptions, and TEA data have been developed. At that stage, the additional process steps and material flows can be incorporated into an expanded LCA in a consistent manner, including the assessment of potential downstream products and the appropriate treatment of the oligosaccharide fraction. Accordingly, this report establishes the LCA of the project process chain up to purified IA and quantifies the environmental performance of the defined system, identifies relevant impact hotspots, and evaluates potential trade-offs associated with the production and purification of IA. The results indicate which process parameters most strongly influence the environmental profile and where further technical development or improved process data are required.

Based on the TEA, all process steps are assumed to take place at a single, centralized location in Central (Western) Europe. Consequently, the analysis does not include the transportation, handling, or temporary storage of intermediate materials between process units. This assumption simplifies the assessment and focuses the analysis on the processing operations. However, any costs, energy requirements, or emissions associated with transporting intermediates would need to be evaluated separately if the process were implemented across multiple locations. The assessment covers the relevant process flows and evaluates the environmental impacts associated with producing the key intermediate, IA, rather than the final products. In the initial assessment, the Hydrolysate is assigned no environmental burden and only the impacts arising from the HemiCoat process cascade are considered. At a later stage, the environmental impact of the hydrolysate is incorporated based on the values reported in a study conducted by OÜ Fibenol and the project partner 2B Srl. in the SWEETWOOD project.[6]

The boundaries selected for the HemiCoat project comprise the Cradle-to-Gate analysis shown in **Figure 4** with an orange background. This includes the C5-sugar enriched hydrolysate, which was obtained from wood through a hydrolysis performed by OÜ Fibenol, a project partner and part of the User Committee of the HemiCoat project.

[6] OÜ Fibenol, *Environmental Footprint of Our Products via Life Cycle Assessment (LCA)*; Breedveld et al., *Life Cycle Assessment of Upcycling Wood Residues into High Value Bio-Based Products with a Novel Fractionation Technology*.

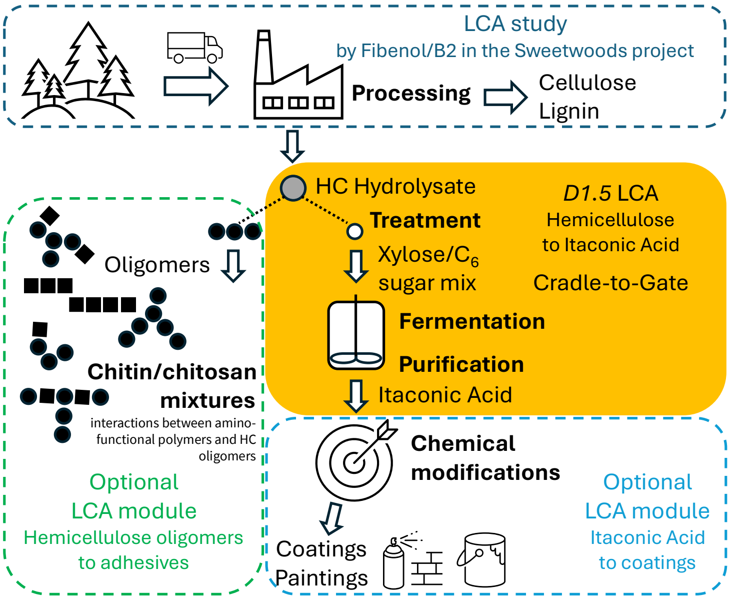

Figure 4. Overview of the *D1.5* LCA system boundaries in the broader context of the HemiCoat project.

The HemiCoat Cradle-to-Gate LCA *D1.5* covers all process flows from the HC C5-enriched hydrolysate from the company Fibenol, the purification into sugar oligomers and monomers, and the fermentation of sugar monomer fraction into IA. The processes upstream of HemiCoat have been assessed through an LCA[7] conducted as part of the SWEETWOOD project. To evaluate the environmental impacts of the complete HemiCoat process cascade, two additional optional LCAs would be required. These assessments have not yet been undertaken, as the necessary techno-economic analysis (TEA) data are not currently available to support a robust evaluation. If conducted at a later stage and combined with the existing results, they would provide a comprehensive overview of the environmental impact of the full HemiCoat cascade.

3.2.2.1. Functional Unit

Defining a system's function and establishing an appropriate functional unit (FU) are critical components in conducting an (attributional) LCA. The functional unit covers qualitative and quantitative aspects of the system's function by addressing key parameters, e.g., what is being assessed, in what quantity, and in what quality. These elements are fundamental to ensuring a valid comparison between different systems. Noteworthy that the parameter time (duration) will be excluded from consideration. For a complex process cascade, which operates as a multi-output process generating multiple products, such as in the HemiCoat project, a distinct functional unit must be defined to enable a meaningful comparative assessment. The functional unit defined in D1.5 is 1 kg of IA with a purity of at least 99%, consistent with the functional unit used in a previous report assessing the environmental impacts of IA production from wheat straw using a biorefinery approach.[8]

3.2.2.2. Cut-off criteria

Mass and energy thresholds are applied as the cut-off criterion in the attributional HemiCoat LCA. Consequently, the cut-off should be viewed as a data collection threshold, below which further

[7] Breedveld et al., *Life Cycle Assessment of Upcycling Wood Residues into High Value Bio-Based Products with a Novel Fractionation Technology*.

[8] Rebolledo-Leiva et al., "Environmental Assessment of the Production of Itaconic Acid from Wheat Straw under a Biorefinery Approach."

data collection is unnecessary due to negligible contributions.[9] This approach intends to account for the average environmental burden associated with the upscaled process cascade based on TEA simulations. By setting a threshold of 0.1 % of the mass or energy inputs, which is expected to be significantly smaller than potential scaling factor errors, minor flows are excluded to streamline the inventory while maintaining the integrity of the results. The use of mass and energy cut-offs ensures that the assessment remains focused on the most significant contributors. Following the guidelines set in ISO 14044[10], the cumulative contribution of all excluded inputs will be verified to be below 5 % of the total environmental impact evaluated by the Global Warming Potential (GWP100).

3.2.2.3. Geographical coverage and regional factors

The geographical scope of the LCA report *D1.5* covers Central (Western) Europe with energy supply from Germany and Belgium, capturing the entire process chain from raw material (hydrolysate from OÜ Fibenol) treatment to intermediate processing and the purification of IA. This assessment follows the Cradle-to-Gate approach, prioritizing regional electricity utilization and industrial processing emissions, but not logistics. Thus, the following regional factors influencing the process chain are identified:

- Feedstock availability and supply chain logistics: The availability of hemicellulose-rich (agro-)industrial by-products in Belgium and Germany dictates sourcing strategies and process feasibility. This is the target of the report *D1.1 Estimation of woody biomass and wood hydrolysate from industry in Belgium and Germany*.
- Energy grid variability: Disparities in energy production portfolios between the two nations may influence the carbon footprint of energy-intensive processing steps.

The energy grid variability is displayed in Error! Reference source not found. comparing the share of energy production by source in Germany, Belgium, and the European Union in 2022.

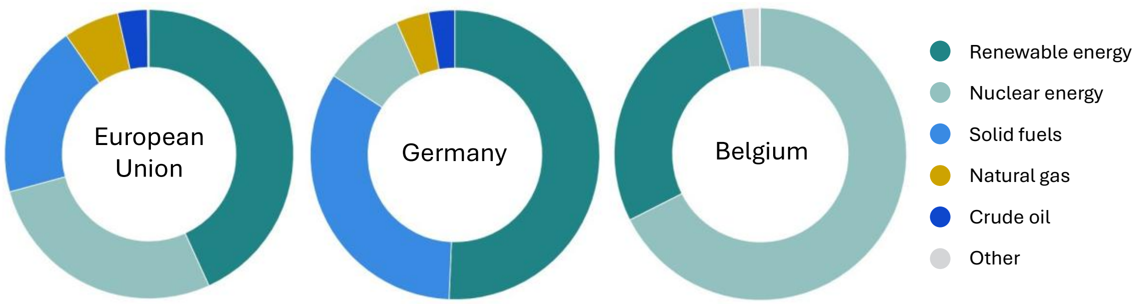

Figure 5. Energy production by share of source in the European Union, Germany, and Belgium in 2022.[11]

When evaluating the geographical scope and regional factors, it is crucial to ensure that the defined boundaries correspond to the study's intended purpose. The geographical boundaries define the relevance of data sources, regulatory frameworks, and energy mixes, all of which influence the overall LCA results. Data sources and input considerations for the LCA are analyzed in the next section.

[9] Laurent et al., "Methodological Review and Detailed Guidance for the Life Cycle Interpretation Phase"; Gradin and Björklund, "The Common Understanding of Simplification Approaches in Published LCA Studies—a Review and Mapping."

[10] "ISO 14044:2006 Environmental Management — Life Cycle Assessment — Requirements and Guidelines."

[11] European Union, "Interactive Publications Shedding Light on Energy in Europe – 2024 Edition."

3.2.2.4. Study definition

The study definition is summarized in **Table 2**.

Table 2. Study definition and scope.

Field	Entry
Product or system	Production of purified Itaconic acid (IA) from a C5-sugar-enriched woody hydrolysate through the HemiCoat process cascade.
Functional unit (FU)	1 kg of IA with a purity of at least 99%.
System boundary	Attributional, cradle-to-gate system boundary ending with production and purification of IA. The boundary covers the C5-enriched hydrolysate, hydrolysate treatment and sugar separation, fermentation, IA purification, relevant utilities, material inputs, recycling and waste treatment. Downstream chemical conversion of IA, use of the oligosaccharide side stream, product use and end-of-life are excluded. Intermediate transport is excluded under the assumed integrated single-site configuration.
Life cycle stages included	Hydrolysate pretreatment/treatment and hemicellulose separation/sugar extraction, inoculum preparation and fermentation, IA purification, treatment of hydrolysate and purification waste, internal recycling of water and ethanol
Geography	Central (Western) Europe, electricity supply modelled for Germany and Belgium, process is assumed to be located at a single, centralized site.
Data sources	Foreground data from the DBFZ technical-economic assessment (TEA), based on laboratory-scale experimental results from HemiCoat WP2 and WP3 and translated into an industrial-scale process simulation. Background data from ecoinvent v3.11 and Agribalyse v3.2, complemented by peer-reviewed literature and industry reports. Upstream hydrolysate information is referenced to the Fibenol/2B Srl. SWEETWOOD assessment when incorporated.
Allocation and cut-off rules	Attributional modelling. The hydrolysate is assigned no environmental burden. Mass- and energy-based cut-off threshold of 0.1% of mass or energy inputs. The cumulative contribution of excluded inputs is to be verified as below 5% of total GWP100 impact. Water recovery is assumed at 55%, ethanol recovery at 95%; unrecovered fractions are treated as process losses/waste.
Product or system studied	The TEA-defined HemiCoat process chain up to purified IA at industrial scale. The assessment does not evaluate IA-derived coatings, surfactants, or other downstream products, nor the hemicellulose-oligomer adhesive route because TEA-based process data were not available.

3.3. Data sources and input considerations

3.3.1. Primary data acquisition

Primary data collection is crucial for ensuring an accurate representation of the processes. In this assessment, data are gathered from a TEA simulation based on laboratory-scale processing experimental data from HemiCoat WP 2 and WP 3, which provide insights into energy consumption, (raw) material utilization, process efficiency, and waste generation under simulated conditions.

3.3.2. Secondary data utilization

Background datasets from reputable sources in Ecoinvent v3.11 and Agribalyse v3.2 database complement the primary data. These databases offer industry-verified life cycle inventory (LCI) data, supporting impact modeling by providing emission factors, energy mix compositions, and material-specific environmental burdens. Existing literature sources, such as peer-reviewed studies and industry reports, provide valuable information on materials, energy use, emissions, and environmental impacts. All secondary data derived from the industrial-scale process simulation of the HemiCoat process cascade in the TEA, performed by the DBFZ, enhance the robustness of the assessment and ensure consistency with established LCA methodologies.

4. Life Cycle Inventory (LCI)

The Life Cycle Inventory (LCI) phase systematically quantifies energy and material inputs, emissions, and waste outputs across the HemiCoat process flow and is outlined in this section. The inventory used in this study is based on the TEA conducted by the project partner DBFZ. The TEA provides the underlying process data, including the main process steps, material and energy inputs, and relevant operational parameters required to characterize the simulated system. Error! Reference source not found. represents a simplified scheme of the processes simulated in the TEA which is the basis for this study. It provides an overview of the main stages within the defined system boundary and illustrates the flow of materials, energy, products, recycling, and waste between them. The scheme is intended to support the interpretation of the LCI by showing how the individual processes are connected, while omitting detailed subprocesses and data flows for clarity.

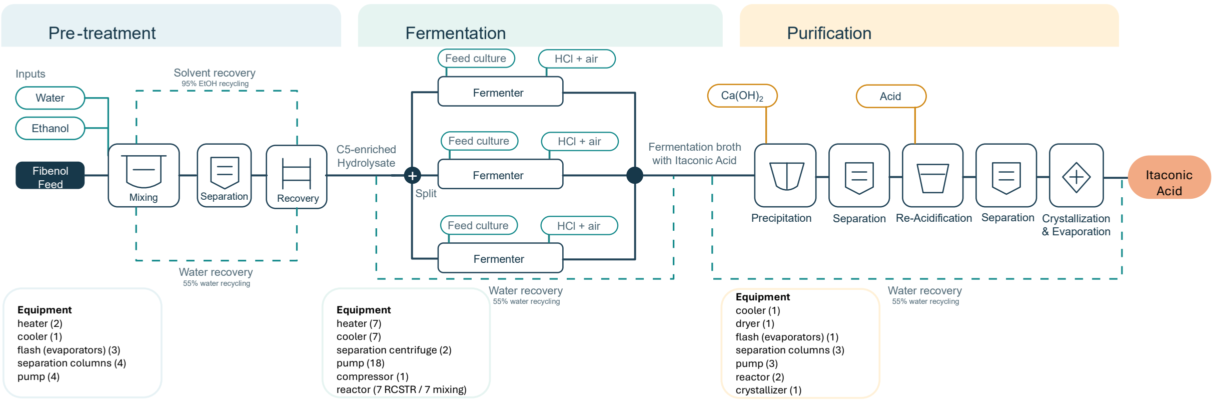

Figure 6. Simplified scheme of the processes simulated in the TEA as the basis of this LCA.

To facilitate interpretation and provide an overview of the process configuration, **Tables 3**, **4** and **5** present a condensed inventory of the material flows of the TEA-modelled processes. The tables combine the main process streams, external inputs, and relevant component flows. Values are based on the reported production rate of 11.67 kg/h of purified IA from the TEA and are normalized to the proposed functional unit of 1 kg IA. For simplification, the life cycle assessment (LCA) was divided into three main process stages: hydrolysate (pre-)treatment, fermentation, and product purification. This subdivision enables the environmental impacts associated with each stage to be assessed separately and facilitates the identification of the main contributors to the overall impact of the process.

Table 6. Environmental impact categories as suggested in the JRC Technical Reports: Supporting information to the characterization factors of recommended EF LCIA methods. lists the material and energy streams of the LCI for hydrolysate (pre-)treatment,

Table 6. Environmental impact categories as suggested in the JRC Technical Reports: Supporting information to the characterization factors of recommended EF LCIA methods. for fermentation, and

Table 6. Environmental impact categories as suggested in the JRC Technical Reports: Supporting information to the characterization factors of recommended EF LCIA methods.for the product purification.

Table 3. Material and energy flows for hydrolysate treatment.

1.1. Treatment of the C5-rich hydrolysate from the Fibenol process				
Input	**Flow Type**	**Flow**	**Amount**	**Unit**
Acetic acid	Elementary	Acetic acid	9.75	kg
Ammonium	Elementary	Ammonium	22.03	kg
Electricity, cooling duty	Product	cooling energy	158.68	kWh
Electricity, pump, 75% efficiency	Product	Electricity, medium voltage {DE} | Cut-off, S	2.41	kWh
Electricity, heating duty separation	Product	Electricity, medium voltage {DE} | Cut-off, S	2.78	kWh
Electricity, flash-system, 50 kW	Product	Electricity, medium voltage {DE} | Cut-off, S	50.00	kWh
Ethanol	Product	ethanol, without water, in 99.7% solution state	9.50	kg
Formic acid	Elementary	Formic acid	0.41	kg
Furfural	Elementary	Furfural	0.12	kg
Glucose	Elementary	Glucose	23.45	kg
Heat, from steam, LP steam for flash	Product	Heat, from steam, in chemical industry	643.30	kWh
Lignin	Elementary	Lignin	15.21	kg
Sodium	Elementary	Sodium	61.34	kg
Sugar-oligomers	Elementary	Sugar-oligomers	12.69	kg
Sulfate	Elementary	Sulfate	61.34	kg
Water, deionised	Product	water, deionised	1217.23	kg
Xylose	Elementary	Xylose	56.38	kg
Output	**Flow Type**	**Flow**	**Amount**	**Unit**
Treated hydrolysate	Product	hydrolysate treated at DBFZ - DE	530.29	kg
Waste hydrolysate	Waste	hydrolysate waste - DE	899.10	kg
1.2. Treatment of the "waste" from the C5-rich hydrolysate treatment				
Input	**Flow Type**	**Flow**	**Amount**	**Unit**
Waste hydrolysate	Waste	hydrolysate waste - DE	899.10	kg
Output	**Flow Type**	**Flow**	**Amount**	**Unit**
Acetic acid	Elementary	Acetic acid	9.66	kg
Ammonium	Elementary	Ammonium	15.09	kg
Ethanol recycled*	Product	ethanol, without water, in 99.7% solution state	8.74	kg
Formic acid	Elementary	Formic acid	0.41	kg
Furfural	Elementary	Furfural	0.12	kg
Glucose	Elementary	Glucose	23.45	kg
Lignin	Elementary	Lignin	15.21	kg
Sodium	Elementary	Sodium	1.09	kg
Sugar-oligomers	Elementary	Sugar-oligomers	12.69	kg
Sulfate	Elementary	Sulfate	61.34	kg
Wastewater	Waste	Wastewater, average treatment of wastewater	346.29	dm^3
Water recycled*	Product	water, deionised	422.68	kg
Xylose	Elementary	Xylose	56.38	kg

* avoided product

Table 4. Material and energy flows for fermentation.

2.1. Preculture to obtain the inoculum for the fermentation				
Input	**Flow Type**	**Flow**	**Amount**	**Unit**
Electricity	Product	Electricity, medium voltage {BE} | Cut-off, S	10.00	kWh
Glucose	Product	glucose	100.00	g
Peptone	Product	Protein feed, 100% crude | fodder yeast | Cut-off, S	10.00	g
Water	Product	water, deionised	1000.00	g
Yeast extract	Product	fodder yeast	10.00	g
Output	**Flow Type**	**Flow**	**Amount**	**Unit**
Inoculum from preculture	Product	Preculture MO	1000.00	g
2.2. Fermentation of the treated C5-rich hydrolysate from the Fibenol process				
Input	**Flow Type**	**Flow**	**Amount**	**Unit**
Air supply	Product	compressed air, 600 kPa gauge	160.33	m^3
Electricity, heater/cooler 90% recovery	Product	Electricity, medium voltage {BE} | Cut-off, S	7.00	kWh
Electricity, centrifuge, TF unit	Product	Electricity, medium voltage {BE} | Cut-off, S	2.72	kWh
Electricity, pumps	Product	Electricity, medium voltage {BE} | Cut-off, S	0.54	kWh
Electricity, compressor	Product	Electricity, medium voltage {BE} | Cut-off, S	3.84	kWh
Electricity, fermentation reactors	Product	Electricity, medium voltage {BE} | Cut-off, S	88.35	kWh
Electricity, RCSTR reactors	Product	Electricity, medium voltage {BE} | Cut-off, S	64.00	kWh
Hydrochloric acid	Product	Hydrochloric acid, without water, in 30%	2.35	kg
Treated hydrolysate	Product	hydrolysate treated at DBFZ - DE	530.29	kg
Inoculum from preculture	Product	Preculture MO	58.90	kg
Water	Product	water, deionised	56.35	kg
Output	**Flow Type**	**Flow**	**Amount**	**Unit**
Biomass from inoculum	Elementary	Biomass	63.80	kg
Carbon dioxide	Elementary	Carbon dioxide, biogenic	6.05	kg
Itaconic acid in fermentation broth	Product	Itaconic acid in fermentation broth	588.99	kg
Nitrogen in air supply	Elementary	Nitrogen, atmospheric	152.82	kg
Dioxygen in air supply	Elementary	Oxygen	0.47	kg

Table 5. Material and energy flows for product purification.

3.1. Purification of Itaconic acid from the fermentation				
Input	**Flow Type**	**Flow**	**Amount**	**Unit**
Cooling energy, COP 3.5	Product	cooling energy	17.22	kWh
Electricity, crystallizer	Product	Electricity, medium voltage {BE}	Cut-off, S	2.43	kWh
Electricity, pumps	Product	Electricity, medium voltage {BE}	Cut-off, S	0.10	kWh
Electricity, Rstoic	Product	Electricity, medium voltage {BE}	Cut-off, S	48.79	kWh
Electricity, centrifuges	Product	Electricity, medium voltage {BE}	Cut-off, S	0.22	kWh
Electricity, flash-system, 10 kW	Product	Electricity, medium voltage {BE}	Cut-off, S	10.00	kWh
Heat, from steam, dryer	Product	Heat, from steam, in chemical industry	0.36	kWh
Heat, from steam, LP steam for flash	Product	Heat, from steam, in chemical industry	74.05	kWh
Calcium (di)hydroxide	Product	hydrated lime, packed	7.52	kg
Itaconic acid in fermentation broth	Product	Itaconic acid in fermentation broth	588.99	kg
Sulfuric acid	Product	Sulfuric acid {RER}	Cut-off, S	9.30	kg
Water	Product	water, deionised	9.30	kg
Output	**Flow Type**	**Flow**	**Amount**	**Unit**
Itaconic acid, purified	Product	purified Itaconic Acid	11.67	kg
purification waste	Waste	Waste Purification - BE	615.10	kg
3.2. Treatment of the "waste" after purification of Itaconic Acid from the fermentation				
Input	**Flow Type**	**Flow**	**Amount**	**Unit**
purification waste	Waste	Waste Purification - BE	615.10	kg
Output	**Flow Type**	**Flow**	**Amount**	**Unit**
Acetic acid	Elementary	Acetic acid	0.09	kg
Ammonium	Elementary	Ammonium	6.91	kg
Ethanol	Product	ethanol, without water, in 99.7% solution state	0.27	kg
Formic acid	Elementary	Formic acid	0.00	kg
Hydrochloric acid	Elementary	Hydrochloric acid	0.27	kg
Sodium	Product	Sodium	0.19	kg
Wastewater	Waste	Wastewater, average treatment of wastewater	253.49	dm^3
Water recycled*	Product	water, deionised	309.49	kg
Xylose	Elementary	Xylose	47.35	kg

* avoided product

4.1. Biomass pretreatment, hemicellulose separation, sugar extraction, and Itaconic acid fermentation

The separation of hemicellulose from biomass and the extraction of sugar mono- and oligomers require an in-depth analysis of:

- Raw material sourcing and processing (based on the approach of Fibenol as a part of the UC).
    - The approach was selected to prioritize easy-to-pretreat hydrolysate with minimal downstream conditioning, backed by a life-cycle record and large-scale availability.
- Energy inputs associated with biomass pretreatment, extraction methods, and the fermentation of IA.
- Chemical consumption and potential emissions from the extraction, the fermentation process, and the purification of IA.
- Waste streams, including unvalorized biomass fractions and effluents, but likewise recycled material flows, such as water and ethanol.

- Water was assumed to be recycled at a rate of 55%, meaning that 55% of the water used in the process was recovered and returned for subsequent use. Ethanol recovery was assumed to be 95%, reflecting a higher recycling efficiency for this solvent. The unrecovered fractions were considered process losses and were accounted for as waste. These assumptions were applied consistently in the LCI to estimate the net resource requirements and associated environmental emissions of the process.

The products of these processes are a concentrated hemicellulose-oligomer fraction, which is not considered in this LCA study and IA. This process cascade is analyzed in *D1.5 Life Cycle Assessment on the production of Itaconic Acid*.

4.2. Logistical and transport impacts

The transportation of (intermediate) materials and products may contribute to the overall environmental impact. However, here, all processes associated with, and operating alongside, the cascade were assumed to take place within a single production plant in central Europe. This assumption was made to reflect an integrated process configuration in which the different process stages are located at the same site and connected through shared material and energy flows. It therefore avoids the need to account for transport between separate facilities and is consistent with the expected use of common infrastructure, utilities, storage, and waste-treatment systems. In addition, locating the processes within one plant may reduce handling requirements, intermediate storage, and material losses, while facilitating the direct transfer and potential reuse of process streams. This assumption also provides a coherent basis for defining the system boundary and modelling the exchanges between the individual stages in the LCI. Any transport or infrastructure requirements that would arise if the processes were located at separate sites were therefore excluded from the assessment, such as:

- Fuel consumption and emission factors associated with transportation (e.g., road, rail).
- Supply chain distribution distances and their influence on carbon footprint.
- Packaging materials and their end-of-life disposal implications.

4.3. LCI data integration and assessment framework

The HemiCoat LCI in *D1.5* integrates empirical and secondary data to provide an evaluation of the environmental performance of the HemiCoat processes. By systematically compiling and analyzing LCI data, the study enables informed decision-making for process optimization and sustainability improvements. Future work may involve refining data precision through additional experimental validation and exploring alternative process configurations for impact reduction.

To obtain a complete picture of the environmental performance of HemiCoat, additional LCAs should be conducted for the subsequent stages of the value chain and for the final HemiCoat end products (see **Figure 4**). The current LCI provides an important basis for assessing the environmental performance of the processes included in *D1.5*, but it does not capture all relevant upstream and downstream activities, such as raw material supply, transportation, product formulation, application, use, and end-of-life treatment for the entire HemiCoat cascade. Assessing these stages would enable the identification of environmental hotspots that may occur outside the current system boundary, but inside the HemiCoat framework, and prevent improvements in one process stage from unintentionally shifting impacts to another.

Further LCAs, as suggested in **Figure 4**, could also be used to compare alternative process configurations, production scales, raw materials, recycling rates, and end-product applications.

This would support a more comprehensive evaluation of trade-offs across different environmental impact categories and provide a stronger basis for selecting the most sustainable process options. Combining the results of these assessments would allow the environmental footprint of the entire HemiCoat process chain to be evaluated from a life-cycle perspective, from the acquisition of raw materials through to the production and potential end-of-life management of the final products.

5. Inventory analysis – Impact assessment methods

For the LCA of the HemiCoat process flows, the software tool openLCA[12] was used. In openLCA, the choice of Life Cycle Impact Assessment (LCIA) method depends on the study's goals, scope, and regional context. Several widely recognized methods are commonly employed, each with distinct advantages.

5.1. Selection of the LCIA method in openLCA

The study *D1.5* applies Environmental Footprint (EF) 3.1, ReCiPe 2016 Endpoint H/A, and IPCC 2021 to provide a comprehensive and complementary assessment of the environmental impacts associated with the HemiCoat processes.

EF 3.1 was selected because it provides a broad set of impact categories within the Environmental Footprint framework, enabling a detailed and consistent evaluation of impacts such as climate change, resource use, acidification, eutrophication, toxicity, and water use. This method is particularly suitable for identifying environmental hotspots across the different stages of the system and for supporting comparisons between alternative process configurations. Moreover, EF method stands out as the preferred choice for studies within the European context due to its standardization, policy alignment, and enhanced comparability. The EF method ensures consistency across assessments, making it particularly valuable for businesses and organizations aiming to comply with EU sustainability regulations and reporting requirements, such as the recently announced Corporate Sustainability Reporting Directive (CSRD).[13] Therefore, the European Commission recommendation (EU) 2021/2279 aims for the use of EF to measure and communicate the LCA performance of products (and organizations), as stated in the Official Journal of the European Union L 471, volume 64.[14] The EF method provides reduced variability by using harmonized datasets and sector-specific guidelines, improving the reliability and transparency of results. This level of standardization is essential for benchmarking environmental performance across industries, facilitating clearer decision-making and policy implementation.

ReCiPe 2016 Endpoint H/A was applied to complement the midpoint-oriented assessment by translating environmental interventions into potential damage to higher-level areas of protection, including human health, ecosystems, and resource availability. The endpoint perspective facilitates the interpretation of results by presenting impacts in terms of their potential consequences rather than only as individual environmental mechanisms. The selected H/A configuration also allows the assessment to be conducted using the assumptions and time horizon defined by the chosen ReCiPe perspective in the assessment software.

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12 GreenDelta GmbH, *OpenLCA*.

13 Operato et al., "Navigating CSRD Reporting: Turning Compliance into Sustainable Development with Science-Based Metrics."

14 European Union, "Official Journal of the European Union L471."

IPCC 2021 was included to provide a focused assessment of the contribution of the system to climate change, expressed as carbon dioxide equivalents. This method is based on the latest available IPCC climate-change characterization factors used in the selected software and provides a transparent basis for comparing greenhouse-gas emissions across process alternatives. Using IPCC 2021 alongside EF 3.1 and ReCiPe 2016 strengthens the assessment by allowing climate-change results to be examined in greater detail while maintaining a broader evaluation of other relevant environmental impacts.

The combined use of these methods reduces reliance on a single modelling perspective and helps identify potential trade-offs between impact categories. Since the methods differ in their characterization models, aggregation levels, and underlying assumptions, their results are interpreted separately rather than directly combined. This combination allows a comprehensive life cycle evaluation focusing on consistency, reproducibility, and comparability in environmental assessments across industries.[15] The interpretation of the results must nevertheless be considered in the context of the defined system boundaries. Notably, the HemiCoat LCA adopts a cradle-to-gate approach and therefore does not include end-of-life scenarios or end-of-life allocation procedures and calculation formulas.[16]

5.2. EF impact categories

The initial step of the assessment was conducted with an analysis of the midpoint impact indicators defined by the Environmental Footprint (EF 3.1) method. All 16 impact categories/recommended methods covered by the EF (JRC technical reports, 2018)[17] are considered to evaluate the environmental impact of the HemiCoat process flow.

[15] European Commission, "Life Cycle Assessment & the EF Methods."

[16] Allacker et al., "The Search for an Appropriate End-of-Life Formula for the Purpose of the European Commission Environmental Footprint Initiative."

[17] Fazio et al., *Supporting Information to the Characterisation Factors of Recommended EF Life Cycle Impact Assessment Methods*.

Table 6. Environmental impact categories as suggested in the JRC Technical Reports: Supporting information to the characterization factors of recommended EF LCIA methods. lists and describes the impact categories at the midterm level.

Table 6. Environmental impact categories as suggested in the JRC Technical Reports: Supporting information to the characterization factors of recommended EF LCIA methods.[18]

Impact category	Indicator	Unit
Climate change	Radiative forcing as Global Warming Potential (GWP100)	kg CO_2 eq
Ozone depletion	Ozone Depletion Potential (ODP)	kg CFC-11 eq
Human toxicity, cancer effects	Comparative Toxic Unit for humans (CTU_h)	CTU_h
Human toxicity, non-cancer effects	Comparative Toxic Unit for humans (CTU_h)	CTU_h
Particulate matter/Respiratory inorganics	Human health effects associated with exposure to $PM_{2.5}$	Disease incidences
Ionizing radiation, human health	Human exposure efficiency relative to U^{235}	kBq U^{235}
Photochemical ozone formation	Tropospheric ozone concentration increase	kg NMVOC eq
Acidification	Accumulated Exceedance (AE)	mol H^+ eq
Eutrophication, terrestrial	Accumulated Exceedance (AE)	mol N eq
Eutrophication, aquatic freshwater	Fraction of nutrients reaching freshwater end compartment (P)	kg P eq
Eutrophication, aquatic marine	Fraction of nutrients reaching marine end compartment (N)	kg N eq
Ecotoxicity freshwater	Comparative Toxic Unit for ecosystems (CTU_e)	CTU_e
Land use	Soil quality index (Biotic production, Erosion resistance, Mechanical filtration	Dimensionless, aggregated index of: kg biotic production/ ($m^{2*}a$) kg soil/ ($m^{2*}a$)
Water use	User deprivation potential (deprivation-weighted water consumption)	kg world eq. deprived
Resource use, minerals and metals	Abiotic resource depletion (ADP ultimate reserves)	kg Sb eq
Resource use, energy carriers	Abiotic resource depletion – fossil fuels (ADP-fossil)	MJ

Starting the HemiCoat LCIA by focusing on these midpoint indicators offers several advantages, primarily due to their simplicity and the availability of well-established calculation methodologies. Midpoint indicators, such as global warming potential, acidification, and eutrophication, are relatively simple to quantify with a lower level of uncertainty than endpoint indicators, such as in ReCiPe 2016. Yet, midpoint indicators provide a detailed analysis of specific environmental impacts of a product's life cycle. With the selected indicators, a clearer understanding of how different processes contribute to specific environmental concerns is described, making them valuable for identifying hotspots and targets for improvement. The selected indicators are widely recognized and standardized, therefore allowing for comparability across studies and sectors. Overall, by focusing initially on midpoints, LCA practitioners can obtain actionable insights without the complexity and uncertainty associated with endpoint assessments, which involve broader, more speculative long-term consequences.

However, since LCA models inherently rely on a variety of assumptions, it becomes essential to employ methods for assessing uncertainty in both LCI and impact assessment. These methods

[18] Fazio et al., *Supporting Information to the Characterisation Factors of Recommended EF Life Cycle Impact Assessment Methods*.

are crucial for effectively conveying the influence of such assumptions on the results, ensuring more accurate and transparent decision-making.

5.3. Data quality and uncertainties based on ecoinvent evaluation

Uncertainty analysis is a crucial aspect of LCA studies, significantly enhancing the reliability and credibility of the results. By systematically identifying, characterizing, propagating, and understanding uncertainties, practitioners can better assess the environmental impacts of products and processes. Uncertainty can arise from various sources, including quantity, model structure, and context, each requiring specific methods for effective management. Effective communication of these uncertainties, through qualitative and quantitative assessments, ensures that stakeholders are well-informed about the confidence and limitations of the results. Data quality was evaluated in openLCA to assess the reliability and representativeness of the inventory data used in the study and is shown in **Table 7**. The ecoinvent Data Quality Systems was selected as flow data quality schema with weighted average aggregation settings and half up rounding mode. The evaluation considered key criteria, including the temporal, geographical, and technological representativeness of the data, as well as their completeness, consistency, precision, and methodological suitability. It is important to clarify that in this evaluation, only secondary data were evaluated based on the quality and applicability of the corresponding database records, which were from ecoinvent. This assessment helped identify data gaps and sources of uncertainty and supported the interpretation of the LCA results. Where precise process-specific data were unavailable, suitable secondary datasets and documented assumptions were used to ensure a complete and consistent model.

Table 7. Qualitative data quality assessment based on ecoinvent datasets.

EF v3.1 category	R	C	T	G	F
Acidification			1		
Climate change			1		
Climate change: biogenic	1		1	1	
Climate change: fossil			1		
Climate change: land use and land use change	1		1		
Ecotoxicity: freshwater	1	1	1	1	1
Ecotoxicity: freshwater, inorganics	1	1	1	1	1
Ecotoxicity: freshwater, organics	2	3	3	3	2
Energy resources: non-renewable					
Eutrophication: freshwater					
Eutrophication: marine	1	1	1	1	
Eutrophication: terrestrial	1	1	1	1	
Human toxicity: carcinogenic			1		
Human toxicity: carcinogenic, inorganics	1	1	1	1	1
Human toxicity: carcinogenic, organics					
Human toxicity: non-carcinogenic	1	1	1	1	1
Human toxicity: non-carcinogenic, inorganics	1	1	1	1	1
Human toxicity: non-carcinogenic, organics	1	1	2	2	1
Ionising radiation: human health					
Land use	2	3	3	3	2
Material resources: metals/minerals	2	1	2	1	1
Ozone depletion					
Particulate matter formation	1	1	1	1	
Photochemical oxidant formation: human health		1	1	1	
Water use	2	2	5	4	1

Note: calculated with ecoinvent 3.11 LCIA Categories/EF v3.1; R=Reliability, C=Completeness, T=Temporal correlation, G=Geographical correctness, F=Further technical correlation; 1... very good to 5... very poor data quality.

It should be noted that the primary HemiCoat process data and the quantitative estimates derived from the TEA upscaling were not included in the present LCA data evaluation because of the high level of uncertainty associated with the TEA assumptions. Consequently, the data-quality assessment presented in **Table 7** is based solely on the qualitative data-quality information provided for the corresponding ecoinvent datasets. It therefore reflects aspects such as the datasets' temporal, geographical, and technological representativeness, but does not quantify the uncertainty of the HemiCoat process data or the upscaling estimates. As a result, some data-quality categories could not be evaluated or are not representative of the complete HemiCoat inventory. The assessment should therefore be interpreted with caution, as it provides an indication of the quality of the background datasets used, rather than a comprehensive evaluation of the overall LCA data quality.

6. Life Cycle Inventory Analysis (LCIA)

Life Cycle Inventory (LCI) analysis is the phase of a Life Cycle Assessment (LCA) in which all relevant material and energy inputs, products, co-products, emissions, and waste outputs associated with the defined system are identified and quantified. The inventory is compiled for each unit process within the system boundary and linked to the selected functional unit, that is 1 kg IA. It includes foreground data collected directly from the process under study, as well as background data obtained from databases, literature, and other secondary sources, and is based on the TEA simulation for parts of the HemiCoat process cascade. The quality, completeness, consistency, and representativeness of these data are important because they directly influence the reliability and interpretation of the subsequent assessment results. The inventory results are converted into potential environmental impacts during the LCIA phase. For this purpose, three complementary LCIA methods were applied: Environmental Footprint 3.1 (EF 3.1), ReCiPe 2016 Endpoint (H), and IPCC 2021. The use of multiple methods provides a broader perspective on environmental performance and reduces reliance on a single modelling approach. Because the methods differ in their characterization models, impact categories, and levels of interpretation, their results are considered complementary and are interpreted according to the specific purpose of each method.

6.1. Environmental Footprint (EF) method

The Environmental Footprint (EF) method is a standardized life-cycle-based framework for assessing the potential environmental performance of products, processes, and organizations. It translates the material and energy flows, emissions, and resource uses compiled in the LCI into a set of environmental impact indicators. By applying harmonized characterization models and defined impact categories, the EF method supports a consistent, transparent, and comparable evaluation of environmental performance across different systems. The framework covers a broad range of environmental mechanisms, including climate change, toxicity, acidification, eutrophication, resource use, land use, water use, and ozone depletion. **Figure 7** presents the environmental footprint results obtained for the HemiCoat project using the EF 3.1 method for the LCIA. In this assessment, EF 3.1 was applied at the midpoint level, where the inventory flows are translated into potential environmental effects such as greenhouse-gas emissions, freshwater ecotoxicity, human toxicity, acidification, eutrophication, resource use, and water use. This approach supports a consistent and transparent evaluation of the HemiCoat processes and facilitates the identification of environmental hotspots within the defined system boundary.

Figure 7. Environmental Footprint results for the HemiCoat processes based on EF 3.1 indicators.

Figure 7 summarizes the calculated (midpoint) impacts associated with the assessed HemiCoat processes. Results are reported in their respective characterization units, as defined by the EF 3.1 method. The main potential hotspot is climate change, with an impact of 52.60 kg CO_2-eq, primarily driven by fossil emissions (52.23 kg CO_2-eq). Freshwater ecotoxicity is also significant at 96.77 CTUe, with inorganic substances contributing the largest share (74.09 CTUe). In addition, non-renewable energy resource use amounts to 1,077 MJ, indicating that energy demand and the associated upstream energy supply are important contributors to the environmental profile.

The results also indicate contributions from land use, water use, eutrophication, human toxicity, ionising radiation, particulate matter formation, ozone depletion, and photochemical oxidant formation. Overall, the findings suggest that reducing fossil energy use and inorganic emissions could provide the greatest opportunities for improving the environmental performance of the assessed processes. However, since the impact categories are expressed in different units and represent different environmental mechanisms, the values should not be directly compared across categories. Instead, each category can only be interpreted individually to identify relevant contributions, areas requiring further investigation, and potential opportunities for process improvement.

6.2. ReCiPe 2016 Endpoint (H) method

ReCiPe 2016 Endpoint (H) was applied to complement the midpoint assessment by translating environmental interventions into potential damage to higher-level areas of protection, namely human health, ecosystem quality, and resource availability. Endpoint results can support the interpretation of the relative significance of different impact pathways, although they generally involve greater modelling uncertainty because several environmental mechanisms are aggregated into damage indicators. **Figure 8** presents the ReCiPe 2016 (H) endpoint results for the assessed HemiCoat processes, grouped into the three areas of protection: ecosystem quality, human health, and natural resources. The results are reported in their respective characterization units and provide an overview of the main environmental contributions within each area.

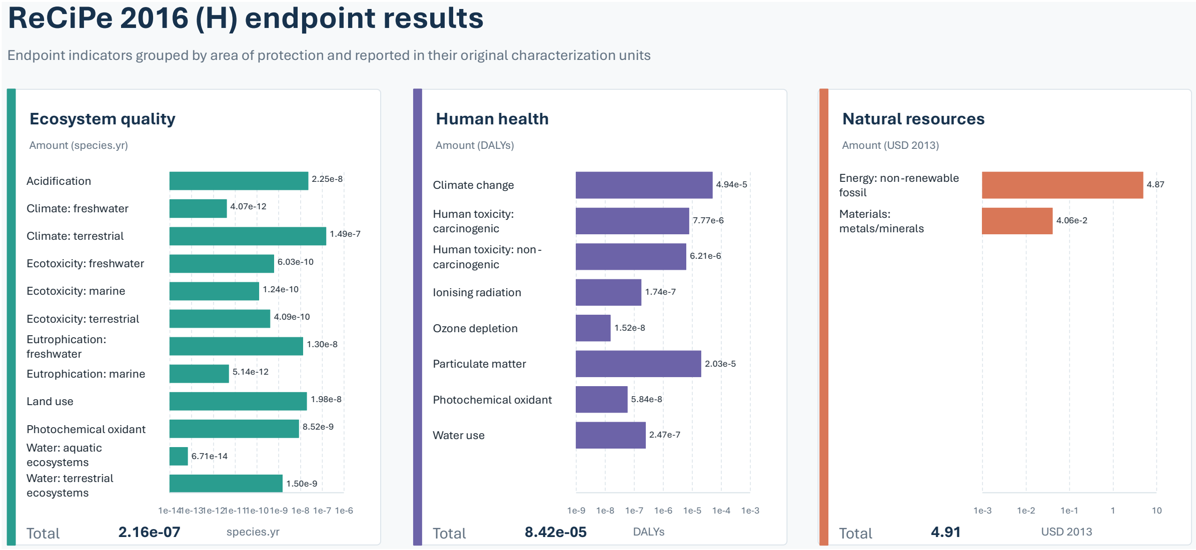

Figure 8. ReCiPe 2016 (H) endpoint impact results for the HemiCoat processes.

The ReCiPe 2016 (H) endpoint assessment indicates that the main potential environmental contributions are associated with climate change, particulate matter formation, and the use of non-renewable fossil energy. For ecosystem quality, the total impact was 2.16 × 10^{-7} species·yr. The largest contribution was climate change affecting terrestrial ecosystems, with 1.49 × 10^{-7} species·yr, followed by terrestrial acidification (2.25 × 10^{-8} species·yr) and land use (1.98 × 10^{-8} species·yr). Freshwater eutrophication also made a notable contribution, while the impacts associated with marine eutrophication and aquatic ecosystem water use were comparatively small. For human health, the total impact was 8.42 × 10^{-5} DALYs. Climate change was the largest contributor, accounting for 4.94 × 10^{-5} DALYs, followed by particulate matter formation at 2.03 × 10^{-5} DALYs. Human toxicity, including carcinogenic and non-carcinogenic effects, contributed additional impacts of 7.77 × 10^{-6} DALYs and 6.21 × 10^{-6} DALYs, respectively. The contributions from ionising radiation, ozone depletion, photochemical oxidant formation, and water use were considerably lower in comparison. The total impact associated with natural resources was 4.91 USD 2013. This result was dominated by the use of non-renewable fossil energy, which contributed 4.87 USD 2013, whereas the contribution from metal and mineral resources was much lower at 0.0406 USD 2013. Overall, the results identify terrestrial climate change, climate-change-related human health effects, particulate matter formation, and non-renewable fossil energy use as the principal areas for further investigation and potential process optimization. The results should be interpreted in the context of the defined system boundary, functional unit, inventory assumptions, and data-quality limitations. In addition, the three endpoint areas are expressed in different units and represent different areas of protection, and therefore, their absolute values should not be directly compared with one another.

6.3. IPCC 2021 method

The IPCC 2021 method is a life cycle impact assessment method focused specifically on the potential contribution of greenhouse-gas emissions to climate change. It applies characterization factors based on the Intergovernmental Panel on Climate Change (IPCC) assessment framework to convert emissions of different greenhouse gases into a common metric, expressed as kilograms of carbon dioxide equivalents (kg CO_2-eq). This enables the climate-change contribution of different substances and process stages to be assessed consistently. **Figure 9** presents the climate change results calculated using the IPCC 2021 LCIA method, expressed as carbon dioxide equivalents and separated into the main characterization time horizons, emission sources, and land-use-change contributions.

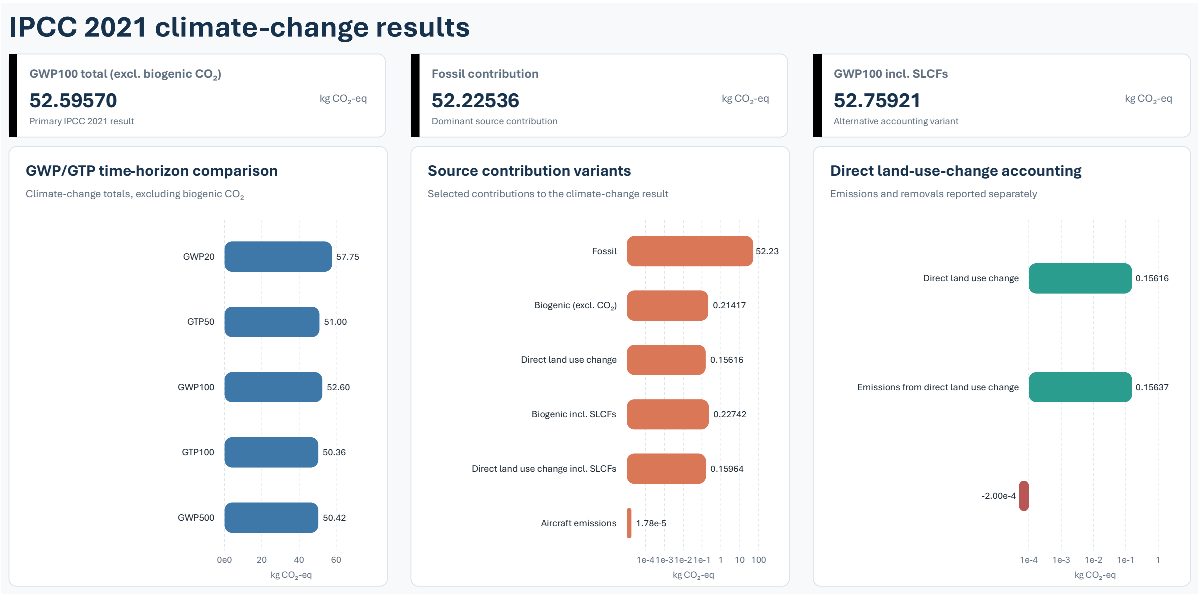

Figure 9. IPCC 2021climate change impact results for the HemiCoat processes.

Figure 9 presents the climate-change results calculated using the IPCC 2021 method. The reference GWP100 result, excluding biogenic carbon dioxide, is 52.60 kg CO_2-eq, while the corresponding result including short-lived climate forcers (SLCFs) is slightly higher at 52.76 kg CO_2-eq. The climate change impact is overwhelmingly dominated by fossil emissions, which contribute 52.23 kg CO_2-eq. Biogenic emissions and direct land-use-change contributions are comparatively small, amounting to approximately 0.214 kg CO_2-eq and 0.156 kg CO_2-eq, respectively. The comparison of time horizons shows that the GWP20 result is highest at 57.75 kg CO_2-eq, whereas the longer-term GWP500 and GTP100 results are approximately 50.42 kg CO_2-eq and 50.36 kg CO_2-eq, respectively. Overall, the results identify fossil greenhouse-gas emissions as the main contributor to the climate-change impact of the assessed HemiCoat processes.

7. HemiCoat LCA in context – A discussion

The interpretation of the HemiCoat LCA results benefits from placing the assessed IA pathway alongside relevant feedstock and production benchmarks. Therefore, this discussion examines the environmental implications of using C5-enriched woody hydrolysate rather than glucose as the fermentation substrate and compares the HemiCoat IA route with selected literature- and database-based reference systems. These comparisons help contextualize the identified hotspots, recognize methodological limitations, and identify priorities for further process optimization.

7.1. Hydrolysate versus glucose as fermentation substrate

The C5-enriched woody hydrolysate applied as feedstock in the HemiCoat process originates from the Fibenol fractionation process. Its environmental performance has already been assessed in a dedicated life cycle assessment study conducted in the context of the SWEETWOODS project. This upstream assessment provides an established basis for characterizing the hydrolysate supply and supports its consistent integration into the broader environmental evaluation of the HemiCoat IA production pathway. The results indicate that the C5-enriched woody hydrolysate used in the HemiCoat process has a lower environmental impact than glucose when used as an alternative substrate for the fermentative production of organic acids. On the basis of the aggregated ReCiPe 2016 endpoint results, the hydrolysate-based route achieves less than 60% of the environmental impact of the glucose-based alternative. The focused climate-change assessment using the IPCC method also shows an advantage for the HemiCoat hydrolysate, with an impact being less than 25% lower than for glucose.[19] This result supports the strategic value of using a hemicellulose-derived side stream as fermentation feedstock, as it can reduce reliance on dedicated, crop-derived sugar substrates while valorizing an existing lignocellulosic process stream. The conclusion should nevertheless be interpreted within the defined modelling assumptions, including the treatment and allocation of upstream hydrolysate burdens, the selected energy supply, and the process configuration. Maintaining this environmental advantage will therefore depend on continued optimization of fermentation performance, energy demand, and downstream recovery.

7.2. Comparative Benchmarking of the HemiCoat IA Production

Comparing the HemiCoat LCA with other LCA results from the literature or database is essential for validating results, contextualizing findings, and benchmarking environmental performance. Such comparisons enable the identification of methodological differences, variations in system boundaries, and key assumptions that may influence outcomes. Furthermore, they facilitate the recognition of industry's best practices and areas for potential improvement, thereby enhancing the robustness of the analysis and supporting more informed decision-making in sustainability research and practice. Because LCA data for IA remain relatively scarce in the scientific literature, comparable studies are limited. This lack of published data makes it difficult to benchmark the environmental performance of the present IA production pathway against other processes, particularly when differences in system boundaries, functional units, background data, and allocation procedures are taken into account. Nevertheless, the study on the *Environmental assessment of the production of itaconic acid from wheat straw under a biorefinery approach* by Rebolledo-Leiva *et al.* (2022)[20] provides a relevant point of comparison, as it also assesses the production of IA from a bio-based resource. Although the two studies differ in feedstock, process configuration, energy requirements, and methodological assumptions, Rebolledo-Leiva *et al.* (2022) offers useful context for interpreting the environmental impacts calculated in the present work. It therefore serves as a valuable reference for evaluating the potential advantages and limitations of bio-based IA production and for identifying the main process stages that contribute to its overall environmental footprint.

The results of the present study are also compared with independently calculated environmental impacts for the production of citric acid. Citric acid was selected as a complementary benchmark

[19] Breedveld et al., *Life Cycle Assessment of Upcycling Wood Residues into High Value Bio-Based Products with a Novel Fractionation Technology*.

[20] Rebolledo-Leiva et al., "Environmental Assessment of the Production of Itaconic Acid from Wheat Straw under a Biorefinery Approach."

because it shares several important characteristics with IA. Both products are organic acids and are produced through microbial fermentation, including fermentation processes based on microorganisms of the genus *Aspergillus*. This similarity provides a more meaningful basis for comparison than a comparison with a chemically synthesized product, because the main stages influencing the environmental profile, such as preparation of the fermentation medium, microbial cultivation, aeration, agitation, separation, purification, and product concentration. The comparison therefore makes it possible to assess whether the environmental impacts estimated for the IA process are within a plausible range for an established, fermentation-based organic-acid production system. Citric acid was also chosen because its production is carried out at a substantially larger industrial scale, with production estimated at approximately 3 million metric tons in 2025.[21] The citric acid industry is consequently more mature than the emerging IA production sector and has benefited from decades of process development, scale-up, operational experience, and optimization. Improvements in strain performance, substrate utilization, fermentation productivity, process control, energy efficiency, and downstream recovery have contributed to the development of industrially optimized production routes. The calculated results for citric acid can therefore serve as an indicative benchmark for evaluating the current IA process and for identifying the potential magnitude of improvements that may be achieved through further process development and scale-up. However, this comparison is not intended to suggest that IA and citric acid are functionally equivalent products or that their environmental impacts can be compared without qualification. The compounds differ substantially in terms of market function, fermentation composition, product concentration, yield, and purification requirements. In addition, differences in feedstock origin, electricity and heat supply, infrastructure, system boundaries, functional unit, and allocation approach may affect the results independently of the production technology itself. The citric acid results are therefore used as a contextual benchmark rather than as a direct measure of the environmental superiority of one product over the other. Within these limitations, comparison with a large-scale and technologically mature fermentation process provides valuable perspective on the environmental performance of IA and highlights the process stages where future optimization could have the greatest effect. **Table 8** presents a comparison of the climate-change indicator, calculated using the EF method, for the production of 1 kg of organic acid. The comparison covers three production routes:

i) the HemiCoat process, which uses wood hydrolysates as the feedstock
ii) the biorefinery process, which is based on wheat straw
iii) an optimized industrial citric-acid production process using sugar as the substrate

By presenting the results on a common mass basis, the table provides an overview of the climate-change impacts associated with these different organic-acid production systems.

Table 8. Comparison of climate change (EF) for the production of 1 kg of organic acid.

Compound	Process	Feedstock	Climate Change (kg CO2 eq), EF	Reference
IA	HemiCoat	Wood hydrolysates, C5-enriched	52.6	
IA	Biorefinery	Wheat straw	14.3	Rebolledo-Leiva *et al.*[22]
Citric acid	Industrial process (optimized)	Sugar	8.35	ecoinvent, Cutoff, S, RoW

[21] mrrse, "Citric Acid Production Outlook."
[22] Rebolledo-Leiva et al., "Environmental Assessment of the Production of Itaconic Acid from Wheat Straw under a Biorefinery Approach."

An LCA comparison is most meaningful when the products being compared are technically identical or functionally equivalent, because this minimizes differences arising from product performance, composition, quality, or application. Comparing the same products ensures that variations in environmental impacts can be attributed primarily to the production systems, raw materials, energy sources, and process conditions rather than to differences in the products themselves. It also supports a consistent functional unit and provides an equal basis for interpreting the results, improving the robustness, transparency, and decision-making value of the comparison. In this context, the three cases in Table 8 represent distinct combinations of feedstock origin and process maturity. HemiCoat (i) and the biorefinery route (ii) rely on alternative lignocellulosic or residual biomass resources and allow an LCA comparison based on a technically identical product, that is 1 kg of IA. Additionally, citric acid production represents a mature and optimized industrial process based on conventional sugar feedstocks. The comparison therefore illustrates how different processing strategies influence the climate-change impact per kilogram of product. However, the results must be interpreted with care because the systems differ in feedstock, pretreatment requirements, fermentation performance, product yields, energy demand, downstream processing, and the treatment of co-products and residual streams. For example, wood hydrolysates and wheat straw do not use first-generation biomass such as crop-derived sugar, but their conversion into fermentable substrates requires additional pretreatment steps and associated energy and material inputs. The optimized industrial citric acid process provides a reference for a technically mature fermentation process, while the HemiCoat and biorefinery cases represent emerging production routes using alternative bio-based feedstocks. The environmental impacts associated with citric acid production were calculated in openLCA using datasets from the ecoinvent database. The calculation used the ecoinvent Cut-off, S, RoW system model together with the EF method, consistent with the settings applied in the comparison presented in Table 8. When the citric acid fermentation process starts from glucose as the substrate, the contribution of glucose to the climate-change indicator is calculated as 1.55 kg CO_2-eq. per kg of citric acid. This value represents the climate-change burden associated with glucose as the modeled input, including its upstream supply chain under the selected ecoinvent settings (Cut-off, U, RoW) using EF as the impact-assessment method. It includes impacts related to the cultivation or production of the glucose feedstock, the associated use of fertilizers and other inputs where applicable, energy consumption, processing, and transport. The value should therefore be understood as the contribution of the glucose substrate within the overall citric acid production system, rather than as the standalone impact of the complete citric acid production process. It is noteworthy that the results shown in **Table 8** should not be interpreted as a direct ranking of the intrinsic environmental performance of the products, since the comparison reflects differences in both feedstock and process development. Instead, the table is intended to place the climate change impact of the investigated routes in a broader context and to indicate the potential importance of future improvements in fermentation efficiency, process integration, energy supply, feedstock utilization, and downstream recovery.

Moreover, our assessment indicates that producing 1 kg of IA via the HemiCoat process requires approximately 6.84 kg of monomeric sugar. For comparison, an optimized industrial citric acid fermentation process requires approximately 1.1 kg of sugar to produce 1 kg of citric acid. On a mass basis, the sugar requirement per kilogram of product is therefore more than 6 times higher for the IA production through the HemiCoat cascade than for the selected citric acid reference process. This difference indicates a substantially lower substrate-to-product conversion efficiency for the HemiCoat process at the current process conditions, in particular due to the fermentation titers. In the LCA, the higher sugar demand contributes directly to increased upstream impacts associated with sugar production, including agricultural inputs, land use, water consumption, and energy use, as well as impacts from the conversion and purification stages. It is therefore an important parameter when interpreting the environmental profile of IA produced via HemiCoat. The comparison should nevertheless be interpreted with care, as IA and citric acid are different products with different molecular structures, production pathways, process conditions, and separation requirements. Consequently, the sugar-to-product ratios are not a measure of process performance or environmental impact. However, the results highlight sugar consumption as a key improvement opportunity for the HemiCoat process. Increasing the conversion yield and reducing sugar losses could significantly lower the process-related environmental burdens of the IA production.

8. Conclusion, strategic recommendations & outlook

8.1. Conclusion

This attributional, cradle-to-gate LCA provides the integrated environmental assessment of the HemiCoat process chain from C5-enriched woody hydrolysate to purified itaconic acid (IA). The assessment is based on the TEA-derived industrial-scale process configuration and uses a functional unit of 1 kg IA with a purity of at least 99%. It therefore provides a decision-support baseline for the process configuration presently defined in HemiCoat, rather than a final environmental qualification of all intended HemiCoat products or applications.

Across the applied Environmental Footprint (EF) 3.1, ReCiPe 2016 Endpoint (H), and IPCC 2021 methods, the results consistently identify energy-related fossil emissions as the principal environmental issue within the modelled system. The EF climate change result is 52.6 kg CO_2-eq per kg IA, of which 52.2 kg CO_2-eq is attributed to fossil emissions. The IPCC 2021 assessment confirms this interpretation: biogenic emissions and direct land-use-change contributions are comparatively small, whereas the GWP20 result increases to 57.8 kg CO_2-eq, underlining the relevance of short-lived climate forcers. The high non-renewable energy-resource use of 1,077 MJ per kg IA further demonstrates that the energy and utility system is central to the environmental profile. However, environmental impact cannot be reduced to climate change alone. Freshwater ecotoxicity is a further material concern, with an EF result of 96.8 CTUe, including 74.1 CTUe associated with inorganic substances. The endpoint results also indicate that climate change, particulate-matter formation, terrestrial acidification, land use, and fossil-resource depletion contribute to potential damage to human health, ecosystems, and resource availability. These findings support a multi-criteria interpretation, as an intervention that lowers greenhouse-gas emissions should also be checked for possible trade-offs in toxicity, water demand, acidification, eutrophication, and resource use.

The comparison with an IA route based on wheat straw (14.3 kg CO_2-eq per kg IA) and an optimized industrial citric acid process (8.4 kg CO_2-eq per kg product) places the current HemiCoat scenario in context. It does not, however, demonstrate direct environmental inferiority of the HemiCoat product system. The literature and benchmark systems differ in feedstock, system boundaries, allocation, background databases, energy supply, process maturity, yields, co-product treatment, and downstream separation requirements. The comparison should therefore be read as a clear improvement signal and a prioritization tool. The HemiCoat route requires substantial optimizations before any comparative environmental claim can be substantiated.

The principal limitation of the present study is also its methodological strength, as the boundary is intentionally aligned with the TEA-supported process design and ends at purified IA. The chemical conversion of IA into coatings, surfactants, or other functional materials, the utilization of the hemicellulose-oligomer stream, inter-site logistics, product use, and end-of-life are not included. In addition, the allocation and burden treatment of the woody hydrolysate, as well as the assumed centralized plant configuration located in Western Europe and recovery rates for water and ethanol, have influenced the results. The study should therefore guide technology development, data collection, and scenario design, but it should not be used as a stand-alone basis for external product-comparison or carbon-footprint claims.

8.2. Strategic recommendations

i) Maintain the C5-enriched woody hydrolysate as the preferred fermentation feedstock and substantiate its circularity benefits

HemiCoat follow-up projects should prioritize the use of C5-enriched woody hydrolysate as the fermentation feedstock, subject to securing a reliable supply and consistent feedstock quality. In comparison with conventional dedicated sugar sources such as glucose, the hydrolysate provides a favorable environmental starting point by valorizing a hemicellulose-rich side stream from woody-biomass processing instead of relying on first-generation sugar. The comparative assessment indicates environmental impacts for hydrolysate relative to glucose as a fermentation substrate. To preserve and substantiate this advantage, further projects should systematically document hydrolysate origin, composition, alternative uses, availability, and the treatment of upstream environmental burdens.

ii) Deploy an integrated, single-location plant configuration and optimize the full process cascade

The single-location production plant should be treated as a strategic design principle. Integrating hydrolysate treatment, fermentation, purification, and waste handling at one site can avoid intermediate transport, packaging, handling, and temporary-storage requirements, while enabling direct material transfer, shared utilities, reduced losses, and more efficient recovery of water, ethanol, heat, and other process streams. The plant should be optimized as one coupled system. Priority actions include heat integration between hot and cold streams, reduced evaporation, flash, cooling, and drying duties, improved crystallization and solids-liquid separation, lower pumping and compressed-air demand, and systematic optimization of recirculation loads. Pinch analysis and updated mass-and-energy balances should be applied alongside the TEA to identify genuine net improvements and avoid shifting environmental burdens between process stages.

iii) Decarbonize utilities while reducing specific energy demand

Fossil emissions and non-renewable energy use are key drivers of the current environmental profile. Consequently, the utility system represents the most important lever for improvement. The future design should assess renewable-electricity procurement, direct electrification where technically feasible, electrified cooling and drying, heat pumps, low-carbon steam, and the use of renewable or residual heat. These measures should be combined with energy-efficiency improvements, since clean energy supply and lower demand reinforce one another.

iv) Scale up to improve productivity and resource efficiency

Scale-up is strategically beneficial because a well-designed industrial process can improve equipment utilization, enable more efficient heat and utility integration, reduce the relative importance of auxiliary inputs and losses, and lower energy and material demands. Higher fermentation titers, yields, and volumetric productivities can reduce reactor volume, aeration, agitation, cooling, inoculum demand, and the downstream purification load per unit of product. Scale-up and experimental work should therefore prioritize strain tolerance to hydrolysate-derived inhibitors, substrate-use efficiency, nutrient demand, pH-control strategy, oxygen-transfer efficiency, batch duration, and compatibility with downstream product recovery. Improvements must be evaluated across the entire process system, as a higher fermentation yield may be offset if it requires materially higher use of nutrients, neutralizing agents, or separation chemicals.

v) Manage chemicals and wastewater

Environmental optimization should address freshwater ecotoxicity, human toxicity, acidification, eutrophication, water use, and climate change together. The process should screen alternatives for acids, bases, nutrients, and other inorganic inputs, minimize salt formation, improve chemical and reagent recovery, and reduce contaminant releases to wastewater. Measured effluent composition, chemical speciation, treatment performance, recovery rates, process emissions, and production losses should progressively be improved.

8.3. Outlook and next steps

Further projects building on HemiCoat should progress from the current screening-level, TEA-aligned assessment to a staged sustainability program. The main development priority should be improving the fermentation process, because fermentation performance determines substrate conversion, IA titre, yield, volumetric productivity, aeration and cooling demand, nutrient and pH-control requirements, reactor capacity, and downstream purification load per kilogram of product. Improving strain robustness towards hydrolysate-derived inhibitors, substrate utilization, oxygen-transfer efficiency, nutrient management, batch duration, and compatibility with product recovery can reduce environmental burdens and production costs simultaneously. In parallel, the assessment should test integrated development scenarios, including the current TEA baseline, improved fermentation productivity and yield, optimized downstream purification and recovery, lower-carbon electricity and heat supply, integrated co-product valorization, and supply-chain configurations. A multi-criteria approach using midpoint indicators, IPCC climate-change results, endpoint results for interpretation, key inventory drivers, uncertainty ranges, and techno-economic implications will help ensure that gains from improved fermentation are retained across purification, utilities, wastewater treatment, and the production system, rather than being offset by burden shifting. A subsequent LCA should extend the present boundary to include upstream hydrolysate supply, logistics, the hemicellulose-oligomer route, and the conversion of IA into coatings, surfactants, and related products. Comparisons with incumbent products should be conducted at the application level using equivalent performance, durability, dosage, and end-of-life conditions. Externally communicated environmental claims should be made only after these system extensions, functional comparisons, sensitivity analyses, and an appropriate review have been completed. Until then, the present LCA provides an innovation roadmap in which the HemiCoat cascade represents a promising circular-bioeconomy route based on C5-enriched woody hydrolysate. Achieving a demonstrably lower-impact industrial value chain will depend mainly on substantial improvements in fermentation performance, supported by low-carbon utilities and efficient downstream processing.

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