Report on LCA, LCC, SLCA

Deliverable 6.3

Author: **Tetiana Onyshchenko**

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List of Abbreviations

Acronyms	Description	Acronyms	Description
(L)**	Large scale	**P34HB**	3HB/4HB copolymer
(R*)	High-pressure reactor	**P3HB**	Poly(3-hydroxybutyrate)
(S*)	Small scale	**PBS**	Polybutylene Succinate
a-	Atactic	**PE**	Polyethylene
AH	Alkaline Hydrolysis	**PEFCR**	Product Environmental Footprint Categories
CEN TR	European Committee for Standardization Technical Report	**PES**	Polyester
CM	Catalysed Methanolysis	**PET**	Polyethylene Terephthalate
CSRD	Corporate Sustainability Reporting Directive	**PGA**	Polyglycolic acid
D	Deliverable	**PHA**	Polyhydroxyalkanoate
EN	European Standard	**PHB**	Polyhydroxybutyrate
ESP	Economic Resource Scarcity Potential	**PHBbio**	PHB produced by cyanobacteria
ESRS	European Sustainability Reporting Standards	**PHBH**	Poly(3-hydroxybutyrate-co-hydroxyalkanoate)
EU	European Union	**PHBHHx**	Poly(3-hydroxybutyrate-co-3-hydroxyhexanoate)
EVA	Ethylene-Vinyl Acetate	**PHBV**	Poly(3-hydroxybutyrate-co-3-hydroxyvalerate)
GA	Grant Agreement	**PLA**	Polylactic Acid
GDPR	General Data Protection Regulation	**PMA**	Polymandelic Acid
GHG	Greenhouse Gas	**PP**	Polypropylene
GRI	Global Reporting Initiative	**PUR**	Polyurethane

Acronyms	Description	Acronyms	Description
GWP100	Global Warming Potential for 100-year time horizon	**PVC**	Polyvinylchloride
i-	Isotactic	**ROP**	Ring-opening Polymerization
ILO	International Labour Standards	**SA**	Social Accountability
IPCC	Intergovernmental Panel on Climate Change	**SCP**	Sustainable Consumption and Production
ISO	International Organisation for Standardisation	**SDG**	Sustainable Development Goal
KPI	Key Performance Indicator	**SETAC**	Society of Environmental Toxicology and Chemistry
LCA	Life Cycle Assessment	**SLCA**	Social Life Cycle Assessment
LCC	Life Cycle Costing	**SMETA**	Sedex Members Ethical Trade Audit
LCI	Life Cycle Inventory	**TD**	Thermolytic Distillation
LCSA	Life Cycle Sustainability Assessment	**TPS**	Thermoplastic Starch
LDPE	Low-Density Polyethylene	**TPU**	Thermoplastic Polyurethane
MF	Material Flow	**UN**	United Nations
MFA	Material Flow Analysis	**UNEP**	UN Environment Programme
MPs	Microparticles	**VC**	Value-chain
NCs	Nanocapsules	**W2BC**	**Waste2BioComp**
NR	Natural Rubber	**WP**	Work Package
NREU	Non-Renewable Energy Use	**ZDHC**	Zero Discharge of Hazardous Chemicals

1. Introduction

The main objective of Task 6.3 was the life cycle sustainability assessment (LCSA) of the **W2BC** developed solutions, comparing with conventional products, by means of life cycle assessment (LCA), life cycle costing (LCC) and social LSA (SLCA), according to UNEP/SETAC Guideline, and ISO 14040/14044 and EN 16760/ISO 22526 standards.

The LCA of products and processes is analysed based on the production chain and evaluated with regards to its environmental aspects. Two main approaches were followed in **W2BC**: on the one hand the circular approach cradle-to-cradle, and on the other hand a cradle-to-grave approach, which reflects the complete life cycle of the product. According to ISO 14040/ISO 14044, the approach includes the definition of the objective of the investigation framework, the life cycle inventory analysis, impact assessment and evaluation, determined by its product system. Finally, an analysis of the environmental impact in the form of the CO_2 footprint was prepared.

The LCC analyses the economic efficiency of the processes and comprehensively considers all costs that arise from supply, production, use and recycling or disposal. The LCC only evaluates the negative costs; profits are not part of the LCC. The evaluation of the LCC is incorporated into the LCSA.

The SLCA assesses the social costs during the life cycle of a product. While the environmental costs are always negative, the social impact can be both negative and positive. The analysis and evaluation of the negative and positive effects are included in the final evaluation of the LCSA.

At earlier stages, the LCA of separate development steps (simplified LCA) was performed based on principles of eco-design, i.e., the product systems from WP1-WP5 were first analysed and evaluated separately in terms of their CO_2 footprint. Finally, all relevant steps have been optimized and joined in the respective product development chains, i.e., value chains (VCs). During the development of each production chain, the estimation and improvement of crucial, material- and process-related influencing factors have been implemented. Consecutively, LCC analyses have been performed for all VCs in the system boundaries used for LCA, i.e., in the same system boundaries. Finaly, SLCA aspects of new bio-based solutions have been estimated using stakeholder assessment approach.

More detailed information regarding principles of LCSA used in the **W2BC** project and related results are presented below.

2. Life Cycle Sustainability Assessment

The modern world is currently confronted with countless environmental challenges. The importance of an in-depth consideration of sustainable development is becoming increasingly relevant and obvious.

Today, there are many relevant methods that are aimed at developing the foundations of sustainable development. Among these methods, ecological design and LCSA occupy a significant place. These concepts are equally crucial for minimising the negative impact of human activity on the environment and promoting sustainable development in a comprehensive manner. The integration of ecological design and LCSA opens exciting new opportunities for creating modern and more innovative solutions. By using these modern tools and combining them, it becomes possible to combine creative and diverse technical approaches to achieve the most environmentally friendly effect. At the same time, it is possible to ensure economic feasibility and realistic assessment of social acceptability. The results and recommendations obtained can be used in various industries and production sectors.

Ecological design, or eco-design, includes principles and practical tasks that are directly aimed at creating products and processes with the lowest, minimal environmental impact. The results are achieved through optimising the choice of materials, controlling the use of energy and reducing the amount of energy used. Waste generation is also predicted and targeted reduced.

Eco-design not only contributes to the conservation of natural resources but also helps to reduce the environmental footprint of products throughout their entire life cycle.

2.1. Method description

LCSA refers to the evaluation of all environmental (LCA), social (SLCA), and economic (LCC) impacts (Figure 1) and benefits in decision-making processes towards more sustainable products throughout their life cycle.

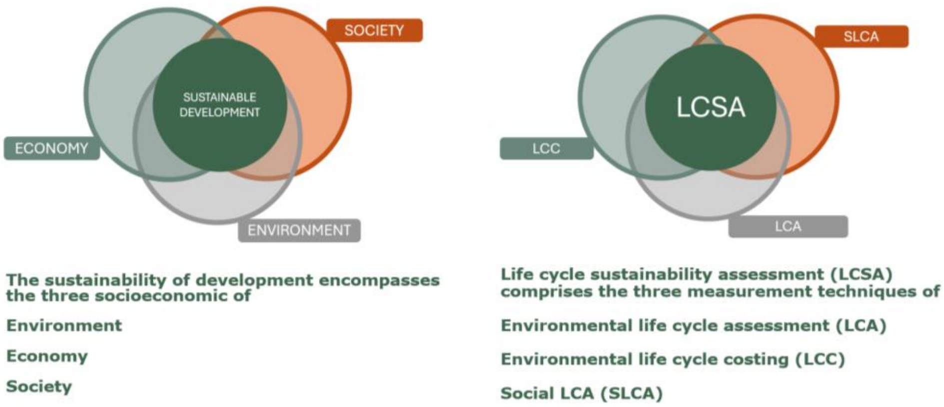


Figure 1 Schematic demonstration of what sustainable development and LCSA encompass.

Increasing interest in developing methods to better underset and address the impacts of products along their life cycle has been stimulated by a growing global awareness of the importance of protecting the environment, an acknowledgement of the risks of trade-offs between possible impacts associated with products (both manufactured and consumed), and the necessity of considering climate change issues and biodiversity from a holistic perspective. Potential and future decision-makers, stakeholders, enterprises and consumers can benefit from LCSA in the following ways:

- enables practitioners to organize complex environmental, economic and social information and data in a structured form
- helps in clarifying the trade-offs between the three sustainability pillars, life cycle stages and impacts, products and generations by providing a more comprehensive picture of the positive and negative impacts along the product life cycle

- show enterprises how to become more responsible for their business by considering the full spectrum of impacts associated with their products and services
- promotes awareness in VC actors for sustainability issues
- supports enterprises and VC actors to identify weaknesses and enable further improvements of a product life cycle. For instance, it supports decision-makers in enterprises to find more sustainable means of production and in designing more sustainable products
- supports decision-makers to prioritize resources and invest them where there are more chances of positive impacts and less chance of negative ones
- helps decision-makers choose sustainable technologies and products
- can support consumers to determine which products are not only cost-efficient, eco-efficient or socially responsible, but also more sustainable
- stimulates innovation in enterprises and value chain actors
- has the potential to inform labelling initiatives
- communicating transparent LCSA information helps enterprises to raise their credibility
- provides guiding principles to achieve Sustainable Consumption and Production (SCP).

LCSA is the result of combining three independent methodologies: LCA assessing the environmental performance, LCC analysis addressing the economic impacts of products, and SLCA including the social perspective in the assessment being a young methodology still in development, although it has been validated in real case scenarios. Only by considering the three pillars of sustainability can the sustainable development of products and activities be ensured, and the UNEP/SETAC guidelines along with the ISO 14044 and EN 16760/ISO 22526 standards, which are based on the international ISO 14040 standard for LCA, are adapted to account for economic and social impacts as recommended by the United Nations (UN).

2.1.1. Life Cycle Assessment (LCA)

The LCA is a method used to assess the environmental aspects associated with a product throughout its life cycle. As defined in ISO 14040 and 14044, LCA (i.e., environmental impact) is conducted in four stages, which are usually interdependent (Figure 2):

- Purpose and scope
- Inventory of resource use and emissions
- Impact assessment
- Interpretation

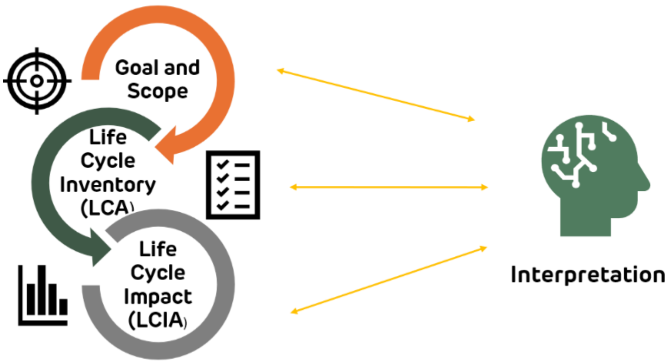


Figure 2 The four stages of LCA.

2.1.2. Life cycle costing (LCC)

LCC is the oldest of the three life cycle techniques. Developed originally from a strict financial cost accounting perspective, in recent years LCC has gained importance. In essence, LCC is the total sum of all costs that are directly associated with a product throughout its entire life cycle - from the extraction of resources in the supply chain through the supply chain to use and disposal. It usually consists of four steps (Figure 3):

- Defining the purpose, scope and functional unit
- Inventory of costs
- Aggregation of costs by cost categories
- Interpretation of the results

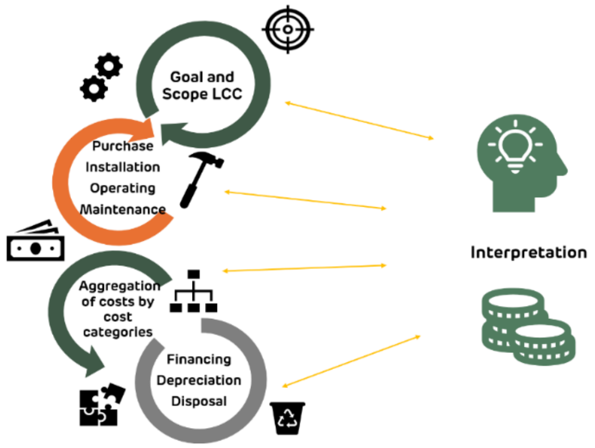


Figure 3 The four stages of LCC.

2.1.3. Social Life Cycle Assessment (SLCA)

SLCA is a life cycle assessment of a product or service that focuses on social impacts and their effects on human well-being. The main goal of this methodology is to identify, assess, and improve social and socio-economic conditions throughout the entire life cycle of a product. SLCA aims to support social justice, human rights, and improve the lives of all stakeholders involved with the product or service. Unlike environmental LCA, which evaluates material and energy flows, SLCA focuses on social impact categories that are assessed through quantitative and qualitative indicators. The methodology usually consists of the following steps (Figure 4):

- Data Collection and Identification of Social Aspects
- Impact Assessment and Identification of Hotspots
- Interpretation of Results and Formulation of Recommendations
- Communication of Results and Implementation of Changes

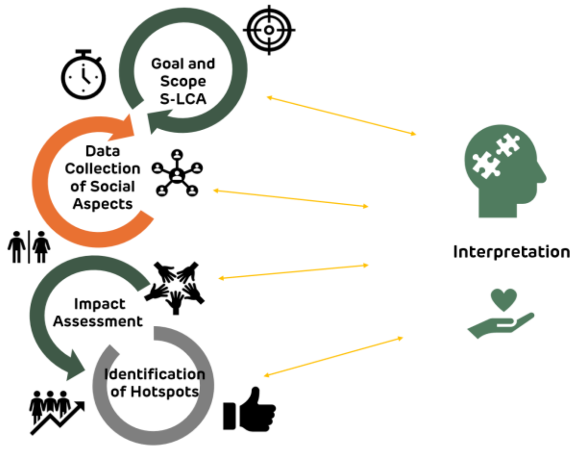


Figure 4 The stages of SLCA.

2.2. Life Cycle Assessment (LCA)

In today's world, the problem of environmental pollution by plastic and microplastic waste has become a global issue. Traditional plastics, which have been made from fossil fuels for decades, are losing their relevance and their long-standing positions due to a long decomposition period, which leads to the accumulation of waste in nature and causes irreparable damage to all ecosystems. The modern scientific world, accepting this challenge, is responding by developing modern technologies to produce new, more environmentally friendly materials. These materials should be able to compete with traditional petroleum materials at all levels.

Among the many biodegradable and biocompatible biopolymers, polyhydroxyalkanoates (PHAs) produced by microorganisms have been highly valued in various fields due to their unique physical and chemical properties. So far, various types of progress have been made in environmental and engineering fields using PHAs.

2.2.1. Purpose and goals

The aim of this study within the **W2BC** project is to predict the environmental benefits that can be achieved by replacing traditional petrochemical polymers with modern, more environmentally friendly PHA-based composites. The assessment will be based on the study of samples obtained in practice in the laboratories of the project partners. Samples are prepared and characterised by the partners, tested for the relevant characteristics and transferred for further implementation directly into the pilot production of finished products from PHAs.

The purpose of the LCA studies is to compare the production of the described products with PHAs, using petrochemical analogues of polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), ethyl vinyl acetate (EVA), polyurethane (PUR), thermoplastic polyurethane (TPU), polyvinylchloride (PVC) with the projected production of bio-based films, rigid packaging, shoe insoles, fibres and coatings for textiles. The results of the LCA show whether bio-based materials are more environmentally friendly than petroleum-based plastics and attempt to explain the rationale behind the results.

2.2.2. General information

Product name: Polyhydroxyalkanoates (PHAs)

Product classification: Description of the research product

1. Foam for insoles:

- Objective: Lightweight, shock absorbing and environmentally friendly footwear materials
- Reference: EVA, PUR or rubber that are not biodegradable
- End use: Used in the production of insoles for sports and casual footwear
- Partner: NORA

2. Plastic films for packaging:

- Target: Sustainable, biodegradable packaging for food and goods
- Reference: PE and PP films that are difficult to degrade
- End use: Use in the packaging industry for the storage and transport of goods
- Partner: PROPAGROUP

3. Production of PHA-based fibres

- Target: Biodegradable PHA-fibres for technical textiles
- Reference: Polyester fibres that do not biodegrade in the natural environment
- End use: Sportswear
- Partners: CITEVE and RIOPELE

4. Finishing for technical textiles:

- Target: Biodegradable coatings for technical textiles
- Reference: Polyester textiles with PVC and PUR based coatings that do not biodegrade in the natural environment
- End use: Sportswear
- Partners: CITEVE and RIOPELE

Geographical scope: European countries

Conformity: The guidelines used for the study are set out in Publications Office of the European Union, 2021 LCA of alternative raw materials for plastics, Rules for determining product environmental footprint categories (PEFCRs), and the link to the LCA method for plastics. The requirements specified in the Economic Resource Scarcity Potential (ESP) method have been developed considering the requirements and recommendations of similar, widely recognised product environmental accounting methods and guidance documents, including ISO 14040 and 14044 standards for life cycle assessment (ISO 14040:2006; ISO 14044:2006).

Compliance with other documents:

- EN 16760:2015 Biological products - Life cycle assessment
- CEN TR 16957:2016 Biological products - Guidance on life cycle inventory (LCI) for the end-of-life stage
- CEN TR 16957:2016 Biological products - Guidance on life cycle inventory (LCI) for the end-of-life stage
- EN 13432:2000 Packaging - Requirements for packaging subject to composting and biodegradation - Test scheme and evaluation criteria for final acceptance of packaging
- EN 14995:2006 Plastics - Evaluation of compostability - Test plan and technical requirements
- EN 17033:2018 Plastics - Biodegradable mulching films for use in agriculture and horticulture - Requirements and test methods
- ISO 14855-1:2012 Determination of the limiting aerobic biodegradability of plastic materials under controlled composting conditions

Methodological limitations: Limited availability of input data and general production information for PHAs.

2.2.3. Field of research

In this context, we outlined a LCA to produce PHAs with a specific focus on energy use and climate change impact. Below is a structured overview of the approach:

Functional Unit

The functional unit of the study is 1 kg of finished PHA product. This unit is chosen as it provides a standard measure for comparing environmental impacts in the production process.

System Boundaries

The system boundaries are defined as "cradle-to-recycling gate", meaning the assessment covers all stages — from the extraction of raw materials ("cradle") to the point where the material exits the recycling process as a secondary raw material. This approach ensures that the life cycle is considered up to the moment of material recovery, including material procurement, production, use (if applicable), and recycling treatment.

At the same time, for certain materials, system boundaries will also be assessed as "cradle-to-gate" and "cradle-to-cradle", depending on the objective of the comparison (Figure 5).

*Figure 5 Stages of the life cycle of a product contemplated in the LCA of the **W2BC** materials.*

System Elements

Input Materials: Biocomponents and other chemicals used for the process are considered as input flows in the LCI. These materials are crucial to assess the energy and material flows entering the system.

Process Focus: Since investigation objects are laboratory- or pilot-scale samples, the end-use and disposal stages might be irrelevant or severely limited. Therefore, the study primarily focuses on:

- Synthesis/Production process: This refers to the production steps involved in creating PHAs and PHA-based materials.
- Energy consumption: Special attention is paid to the energy used in the lab for production and synthesis.
- Waste management: This includes handling laboratory waste, such as chemical reagents and residual materials generated during the synthesis and testing phases. Since laboratory waste is minimal, understanding its specifics is vital for a precise environmental impact assessment.

Transport: Transport processes have been excluded from the system boundaries owing to the unavailability of detailed supply chain data during the research and testing phase.

Selection of Impact Indicators

Only two environmental indicators — Non-Renewable Energy Use (**NREU**) and Global Warming Potential for 100-year time horizon (**GWP100**) — have been considered due to limited input data for production of PHAs and PHA-based items. This selection provides a preliminary environmental impact assessment. Previous research highlights the utility of NREU as an effective environmental performance indicator.

- **NREU**: Assesses the consumption of non-renewable energy during the production process.
- **GWP100**: Evaluates the greenhouse gas (GHG) emissions from the production process and their contribution to climate change over a 100-year horizon. Is crucial for development of sustainable environmental policies and management of emissions (key indicator of environmental impact).

Tools, Databases and Evaluation Methods

To perform the LCI modelling and environmental impact assessment, the following digital tools, databases, and methods were employed:

Databases Used:

- Ecoinvent 3.9.1 (2022): The main LCI database covering production processes for chemicals, electricity, transport, materials, and more.
- Ecoinvent 3.8: A supplementary source to validate or complete missing data.
- U.S. Life Cycle Inventory (USLCI), 2022.Q4: A secondary data source for U.S.-specific materials and processes or as alternatives to European datasets.

Dedicated Software Tool: Umberto 11.11.1 software used to construct LCA models and perform material (MFA) and energy flow analysis (i.e., LCA).

Environmental Impact Assessment Method: Calculation of GWP100 aligning with the most recent recommendations of the Intergovernmental Panel on Climate Change (IPCC).

2.2.4. LCI analysis & LCA impact category results

2.2.4.1. Data collection

As part of the **W2BC** project, several thematic templates were created for data collection, which aimed to collect as much information as possible for the LCI.

Clear and understandable instructions and recommendations on how to fill in the templates were provided (Figure 6).

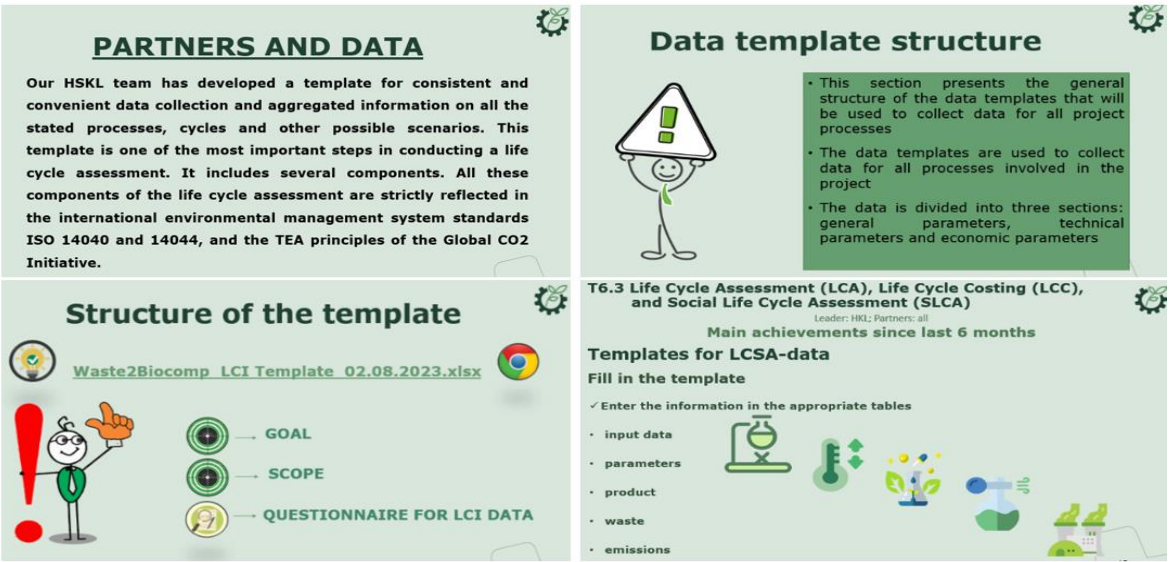


*Figure 6 Instructions on how to fill the template for the LCI in **W2BC**.*

The templates included questions to general product characteristics with additional explanations to each category requested (Figure 7) and questionaries aimed at describing in detail all stages of the production process, materials used, energy consumption, transport flows and product disposal (Figure 8).

*Figure 7 Requested general product characteristics with additional explanations in the LCI-template for **W2BC**.*

Several cycles of interactions with partners and data treatment have been performed according to the following aspects:

- Data Collection: Filling in templates by the **W2BC** project partners during laboratory experiments and pilot processes in production.
- Analysis and Validation: Checking the collected data for accuracy and completeness, correcting possible errors. Updating previously submitted erroneous data.
- Use of Averages: Applying data from the Ecoinvent database and literature, these values were used to fill in gaps in information on energy consumption, to find analogues for some chemicals being missing in the database.

Data Collection Challenges and Limitations

Unfortunately, most of the data collected was minimal since the processes were carried out in a laboratory environment with minimal quantities of components. The laboratory environment is characterised by a limited production scale, which affects the availability and accuracy of inventory data.

Electricity sources

For electricity sources, the report used average figures from the European electricity market based on the Ecoinvent database. This approach was chosen due to the limited availability of specific data on electricity consumption in laboratories. The use of average values provides a certain level of generalisation and allows for comparison of the analysis results with other studies and market standards.

At the same time, several additional electricity source variants from the database, corresponding to different geographical locations of the partners, have also been used in the calculations. This helped to take regional energy consumption characteristics into account and improve the accuracy and relevance of the assessment results.

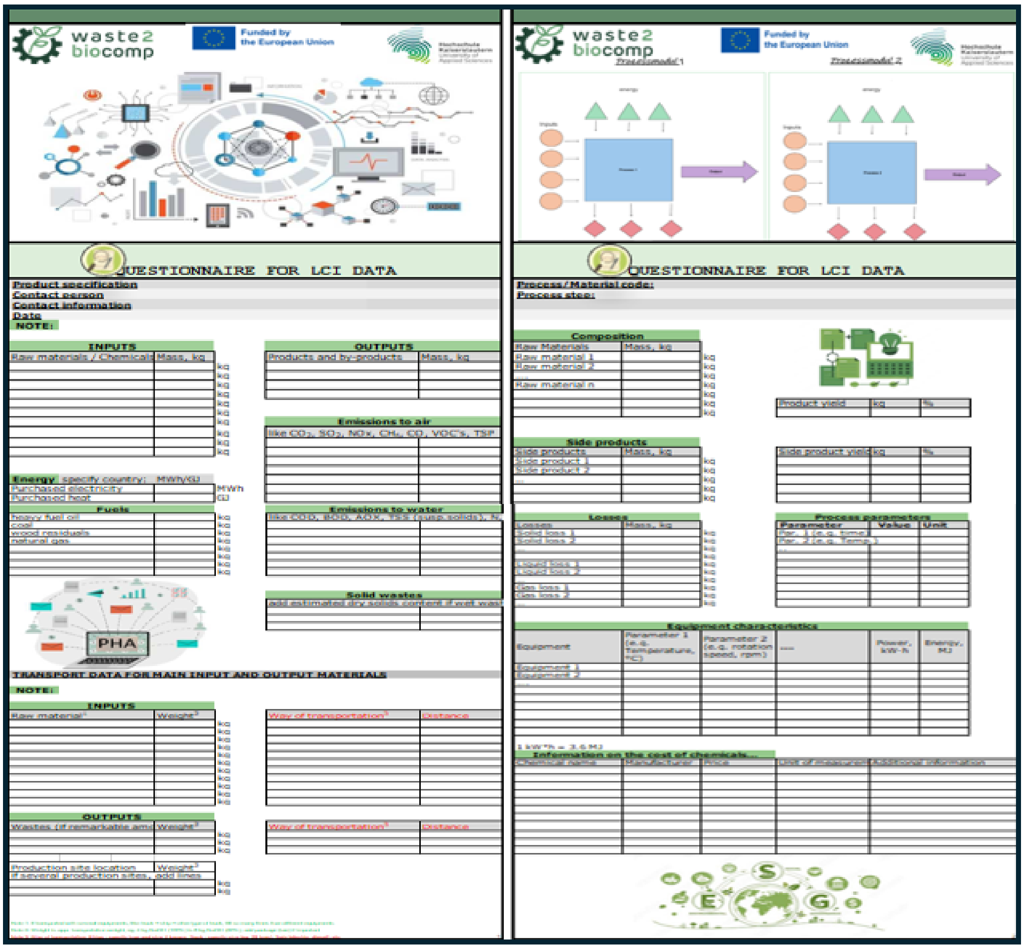


*Figure 8 Detailed product questionaries in the LCI-template for **W2BC**.*

Limitations of the inventory analysis

- Limited data availability: Small amount of data due to the non-industrial scale of production.
- Generalisation of energy data: Use of averages may not reflect specific conditions.
- Impact of laboratory/pilot scale: Laboratory/pilot experiments may not fully replicate industrial processes, which affects the accuracy of the data.
- Confidential data: Because of confidentiality reasons, most process schema with related MF and energy flow cannot be presented in this public report.

2.2.4.2. Results of the LCA

This section presents the LCA results for the upstream and downstream processes. The LCA is responsible for assessing environmental impacts based on the data obtained during the inventory phase (i.e., LCI). The purpose of the LCA is to convert data (e.g., quantities of resources used or emissions) into indicators that reflect environmental impacts. In order to make the sequence of steps in the analysis clearer, the LCA results of intermediate processes and products will be presented first. Then, the final data for the full Cradle-to-Grave chain will also be presented.

Initial PHA synthesis processes

At the initial stages, several synthetic routes for different PHAs performed at different batch levels were analysed using data provided by HSKL. This first screening included synthesis of poly(mandelic acid) (PMA, ~35 g batch), poly(glycolic acid) (PGA, ~35 g batch) and two samples of amorphous/atactic poly(3-hydroxy butyrate) in a small scale (a-P3HB(S*), ~100 g batch) and in a larger scale (a-P3HB(L**), ~5 kg batch) via polycondensation process. It is noteworthy that amorphous a-P3HB can be used to produce soft and flexible products, making it suitable for single-use applications such as packaging. Within the **W2BC** project, this material was considered as a potential material for soft packaging film. A-P3HB produced by ring-opening polymerization (a-P3HB-ROP), on the other hand, is suitable for products where high rigidity, thermal stability, and resistance to mechanical stress are important. As part of the **W2BC** project, it can be considered as a promising material for the manufacture of rigid packaging requiring greater strength and stability. This approach allowed us to consider the specific properties of each material for different types of packaging and expand the possibilities of using PHA products (e.g., foams and coatings).

The results for these systems indicated demand on further reduction of energy consumption. The evaluation of environmental indicators (NREU and GWP100), along with the physicochemical properties of the materials, helped identify the most suitable intermediate product for further research, namely a-P3HB(L**). Based on the recommendations to reduce energy consumption, the upscaled polycondensation process (i.e., ~5 kg batch) was conducted using a high-pressure reactor (a-P3HB(R*)). This resulted in significantly improved energy consumption (Figure 9).

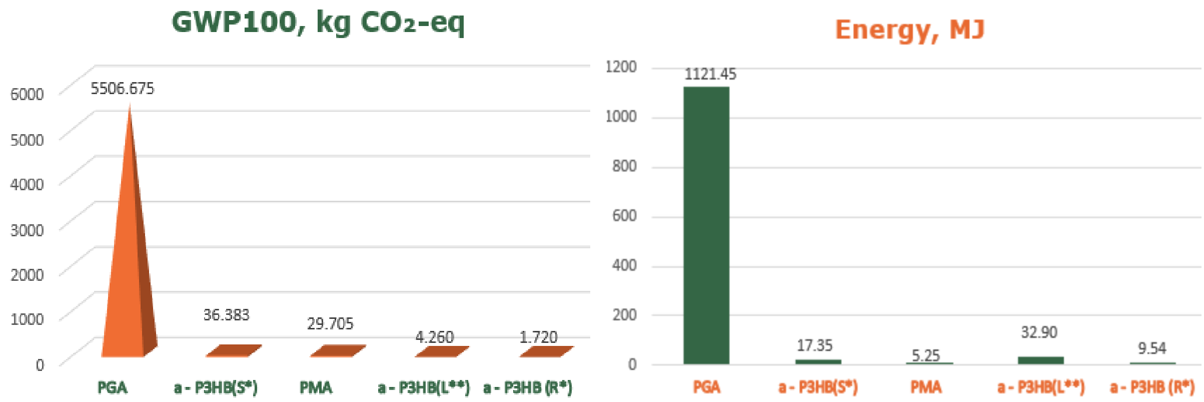


*Figure 9 LCA results for the initial PHA polycondensation processes in **W2BC**.*

In these processes, the functional block (e.g., the intermediate product) has a weight different from 1 kg. Therefore, it is more relevant to calculate the inventory based on the mass of the functional block, as this better reflects the real production conditions. Accordingly, the NREU indicator was calculated according to the actual mass in the process being studied, while the GWP100 indicator was based on 1 kg of the obtained intermediate product.

In addition, comparison of two synthetic routes for a-P3HB, i.e., polycondensation process (a-P3HB) and lactone ring-opening polymerisation (a-P3HB-ROP), have been compared towards their LCA results based on the production of ~1 kg of each product. The related process schema indicating material and energy flows are compared in Figure 10.

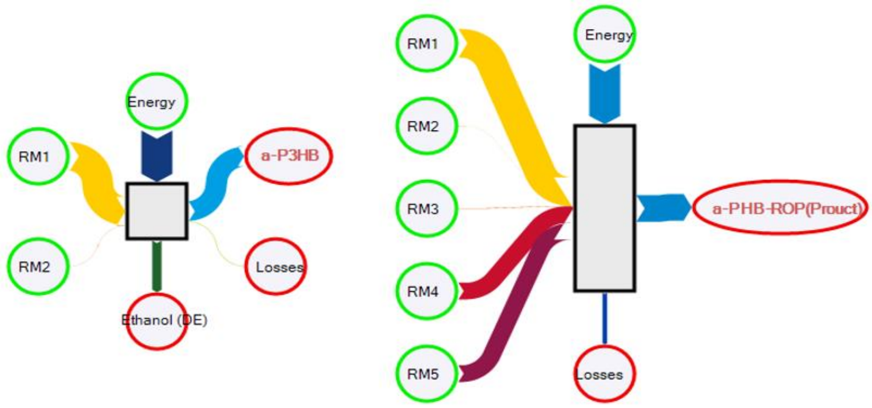


Figure 10 Material and energy flows for a-P3HB (left) and a-P3HB-ROP (right) processes.

The LCA results obtained for these synthetic routes clearly indicated that polycondensation process is more environmentally friendly and requires lower energy consumption (Figure 11). Therefore, this synthetic route was recommended to follow as synthetic route from a sustainability point of view.

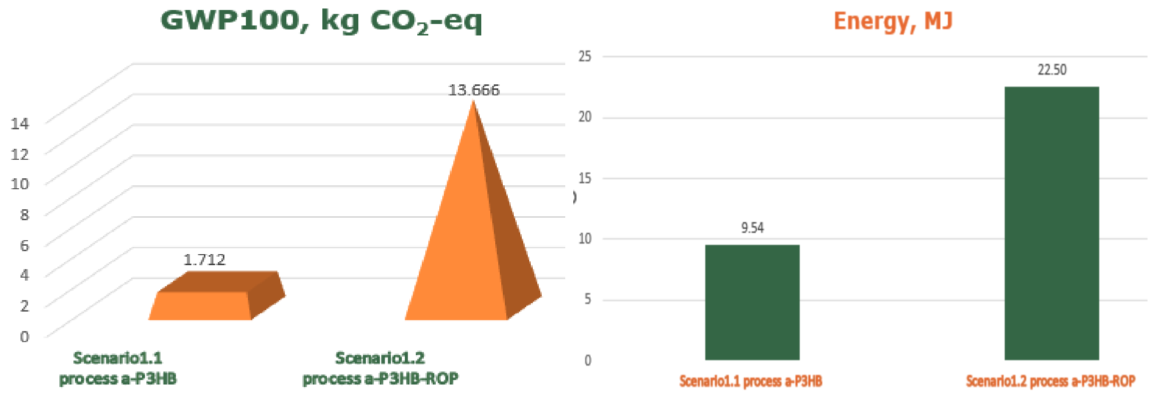


Figure 11 LCA results for the a-P3HB and a-P3HB-ROP production processes.

Production of PHAs

The next step was to process the data from HSKL for the following production processes for various PHAs: i) microbial production of PHB using various strains of cyanobacteria (PHBbio); ii) blending of commercial isotactic P3HB (i-P3HB) with the intermediate a-P3HB, previously obtained via energy-optimized polycondensation route, in extruder, and iii) their mixing in a solution using a reactor followed by removal and recovery of solvent. In addition, the resulting materials have been modified by incorporating commercial P34HB (a 3HB/4HB copolymer), either as a third component or as an alternative to a-P3HB. The inclusion of P34HB significantly enhanced the elasticity and biodegradability of the material. This modification led to a notable improvement in the performance of the previous samples, particularly in terms of mechanical flexibility and environmental degradation potential. The LCA results for selected representative systems are presented in Figure 12. Due to confidentiality reasons, PHAs containing synthetic a-P3HB developed in **W2BC**, as well as commercial P34HB, are specially coded, i.e., PHA.A.2.3.1.4, PHA.A.2.3.1.1, PHA.K.3.3.1.4, PHA.C.3.3.1.4, respectively.

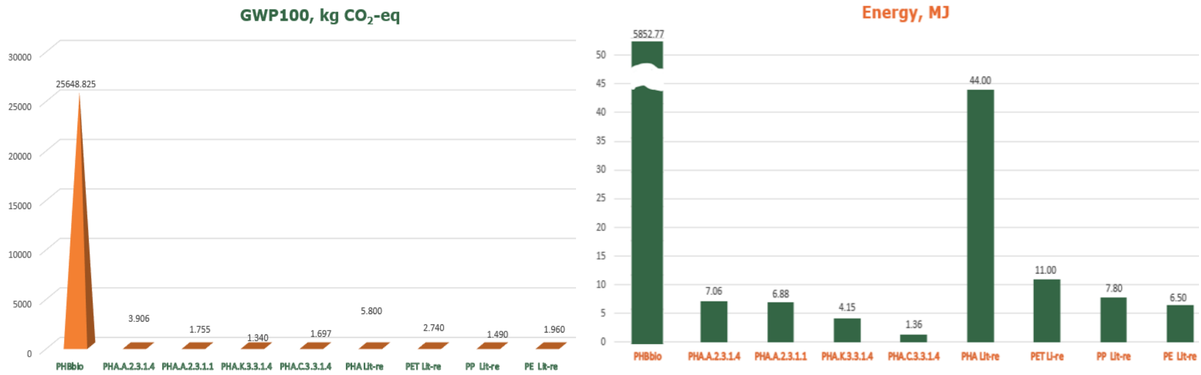


Figure 12 LCA results for PHBbio and PHA.A.2.3.1.4, PHA.A.2.3.1.1, PHA.K.3.3.1.4, PHA.C.3.3.1.4 production processes.

Currently, the production and extraction of microbial PHAs using cyanobacteria remain at the laboratory scale. In the presented case, the functional units range from 1 to 1.5 mg per production cycle. Despite the scalability of this process was empirically confirmed, no obvious improvement of LCI-results was achieved and further optimisation of this technology, especially regarding the yield of the product, is required. In contrary, the LCI-data for PHA-blends have been calculated for 1 kg of finished product.

Despite this difference in functional units applied for routes based on biotechnological and chemical synthesis of PHAs, it is clearly seen that all processes for production of PHAs based on implementation of chemically synthesised a-P3HB are obviously more sustainable and preferable for the achievement of the project goals. It is noteworthy that the investigated systems PHA.A.2.3.1.4, PHA.A.2.3.1.1, PHA.K.3.3.1.4, and PHA.C.3.3.1.4 showed lower values of GWP100 and NREU compared to actual literature data for PHAs. Moreover, some of them (especially PHA.K.3.3.1.4 and PHA.C.3.3.1.4) showed improved sustainability compared to classical petroleum-based polymers PET, PP, and PE, when compared with available literature data.

Production of PHA-based microparticles (MPs)

According to the data provided by partner UDC, miniemulsion/evaporation-based process without (MPA) and with recovery of solvent (MPB) was used for the production of PHA-based MPs. The technological process chain outlined here aims to produce micro- or nanoparticles containing biologically active compounds, such as curcumin and quercetin, using a P3HB matrix. The primary objective was to develop biodegradable microcapsules capable of controlled release, with potential applications across fields like packaging, shoes, textiles, pharmaceuticals, agriculture, and other high-tech industries. Currently, production remains at the laboratory level and has not yet reached industrial scale. At this stage, the functional unit of 0.0157 kg per production cycle was set. The LCA results are presented in Figure 13.

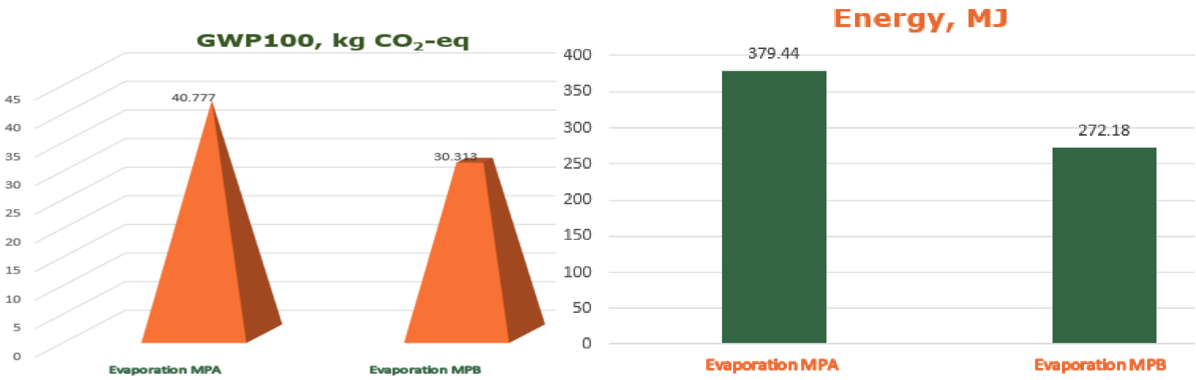
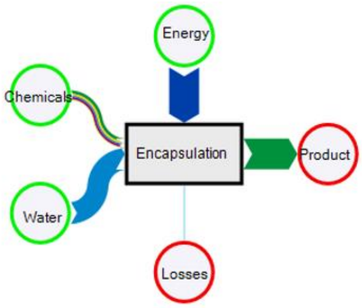


Figure 13 LCA results for the miniemulsion/evaporation processes MPA and MPB.

Unfortunately, miniemulsion/evaporation process MPA used for manufacturing of functional MPs is highly energy intensive and resulted in very high GWP100 value. Recovery and reuse of organic solvent obviously reduced the environmental impact and energy consumption. However, both values remained still too high. Demand on significant energy and chemical inputs could probably even limit its viability for large-scale industrial applications without further process optimization.

Synthesis of bio-based nanocapsules (NCs)

To improve material performance and/or functionality, the **W2BC** project (WP1-WP3) considered the addition of functional NCs, which can provide packaging and insole materials with additional functions, like antibacterial protection or extending the shelf life of products and are also promising for the textile industry. The development of NCs may affect various aspects of production, including the need for additional processing steps and the likely environmental impact. Antimicrobial/antifungal bio-based core-shell tiny capsules (i.e., NCs) have been developed by partner IVW. Incorporation of such NCs in targeted products should allow an effective control of microorganisms while minimising the use of synthetic actives and reducing environmental impact. Unfortunately, the data on the implementation of the obtained samples of NCs in the production of packaging films, antimicrobial insoles, and textiles could not be provided. Therefore, only environmental impact and energy consumption for the production processes for selected NCs have been analysed. Representative process scheme and related LCA results are presented in Figure 14 on the example of zein NCs with Spanish Oregano Oil as active, based on 1 kg of finished product. It is noteworthy that both NREU and GWP100 resulted in quite low values indicating high sustainability of their production.



Equipment	Energy, MJ
Energy	0.12

Polymer/Scenario	GWP100, kg CO_2-eq
Process NCs	0.731

Figure 14 Total MF and Energy Flow with LCA results for zein NCs with Spanish oregano oil.

Production of rigid plastics

According to the data provided by partner UDC, two different process scenarios were carried out in laboratory conditions to produce rigid plastic items made of different PHAs provided by partner HSKL. Unfortunately, until the end of the project the production of rigid plastics remained at the large laboratory scale and did not reach the technical/pilot scale.

In the first process (RIGID PLASTIC A), a chain of steps involving drying, milling, and hot pressing has been used. Hot pressing should ensure high strength and rigidity of the final product.

In the second process (RIGID PLASTIC B), drying and injection moulding steps have been used. Injection moulding is popular for manufacturing plastic products, because it allows creation of precise parts with complex shapes making it suitable for economically beneficial mass production. The technology is also effective for large-scale production of PHA-based plastic products, particularly to produce rigid packaging.

The LCA results for both processes are compared in Figure 15 based on 1 kg of finished product.

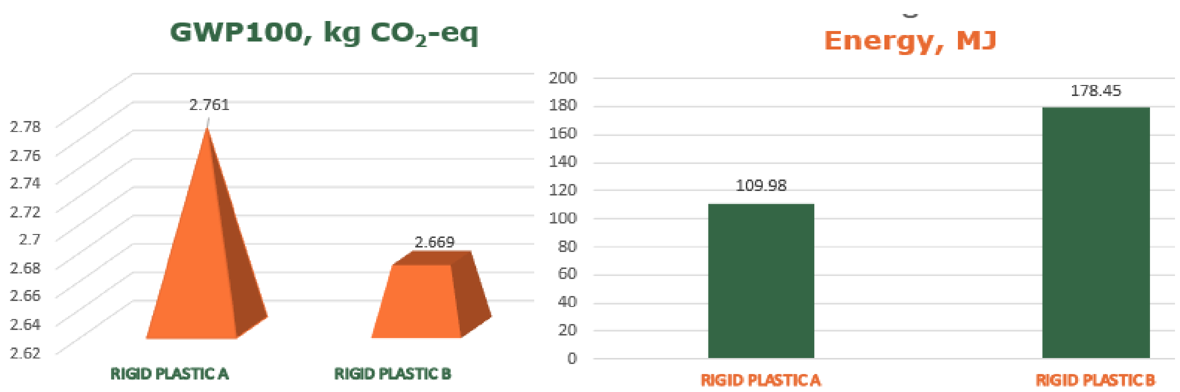


Figure 15 LCA results for the RIGID PLASTIC A and RIGID PLASTIC B processes.

Despite similarly low environmental impact values (i.e., GWP100 values) have been obtained for both production processes (using compression and injection moulding), both required a high energy consumption, especially in the case of injection moulding.

Production of PHA-based films

As part of the project, laboratory samples of synthesised PHAs were used to produce films on a pilot-scale blow extrusion line operated by partner PROPAGROUP. The three following material compositions have been selected for investigation:

- PHAs - 50% PHA and 50% LDPE
- PHAs* - 70% PHA and 30% LDPE
- PHAsK - 70% PHA and 30% PLA

The objective of selecting these specific ratios was to assess how varying proportions of biopolymers (PHAs, Polylactic acid - PLA) and conventional low-density polyethylene (LDPE) influence the mechanical properties, thermal resistance, and environmental performance of the resulting films.

Notably, the PHAsK composition demonstrated improved processing stability, reduced brittleness, and satisfactory structural homogeneity. These characteristics highlight its potential in the field of sustainable packaging.

All three material scenarios were benchmarked against literature data for LDPE. Additionally, comparative data from other reference materials were included, such as bio-based polybutylene succinate (PBS) and a representative from the general class of PHAs. This comparative approach enables a more comprehensive understanding of the advantages and limitations of PHA- and PLA-based materials and supports the development of well-grounded conclusions regarding their industrial viability for use in packaging applications.

The LCA results for production of respective PHA-based films are presented in Figure 16 based on 1 kg of finished product.

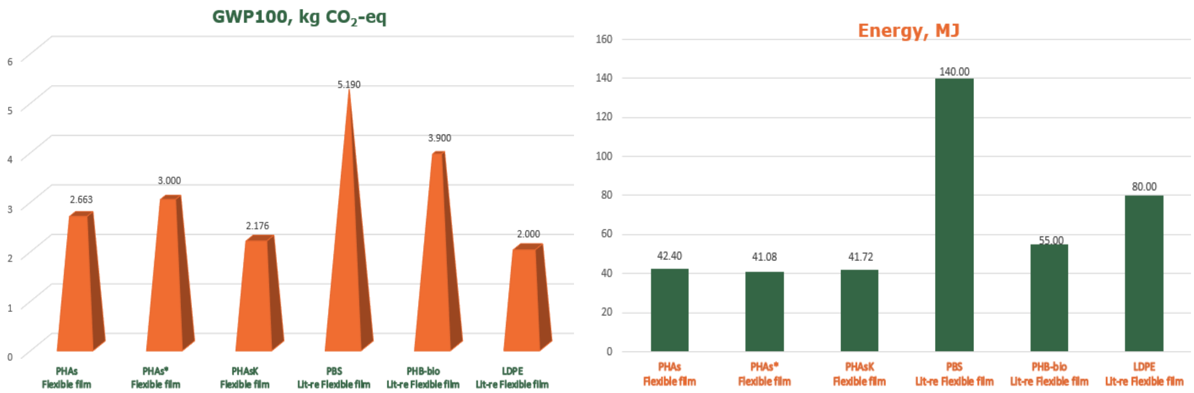


Figure 16 LCA results for the PHAs-/PHAs-/PHAsK-based film production processes.*

All investigated systems showed improved GWP100 and NREU values compared to literature data for films made of commercial bio-based P3HB and PBS, and petroleum-based LDPE, whereas PHAsK system, containing 30% PLA, provided the most beneficial LCA results.

Production of PHA and PUR Foams

Within the scope of the project, PHA-based foamed materials have been produced on the industrial lines of partner NORA using PHA samples synthesised at a large laboratory scale provided by partner HSKL. First, two following formulations based on the material PHA.A.2.3.1.4 were selected for LCA evaluation related to replacement of a common mineral filler with a bio-based one:

- PHA HN — with mineral filler,
- PHA HN* — with bio-based filler.

A parallel study was also conducted using two compounds based on an industrial PHA-based formulation for foam production:

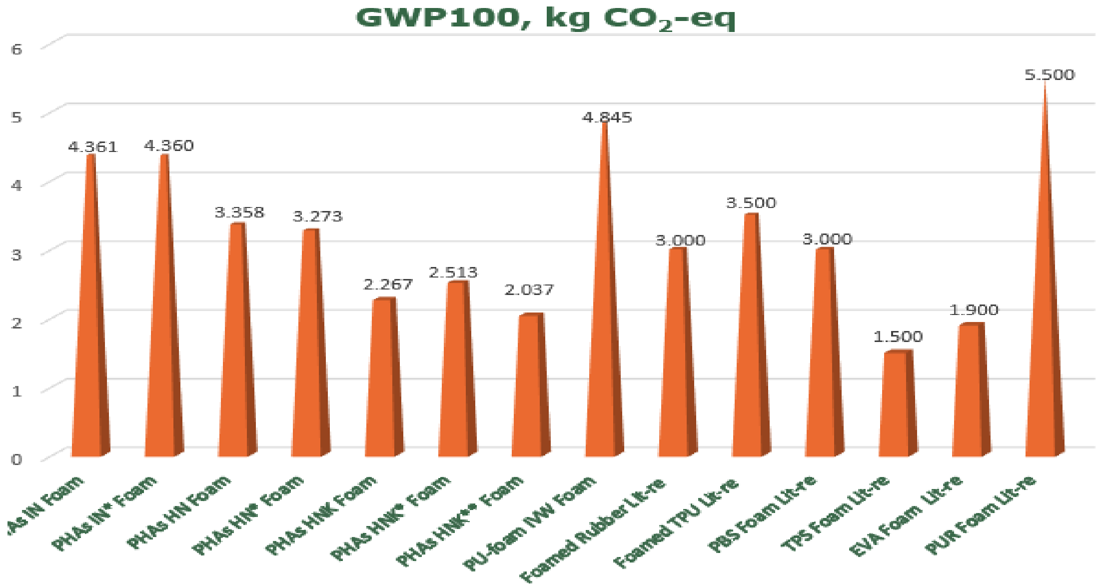
- PHA IN — with mineral filler,
- PHA IN* — with bio-based filler.

In addition, special attention was paid to the three different formulations based on PHA-compound PHA.K.3.3.1.4 varying in type and/or content of a filler:

- PHAs NHK - bio-silica 29.4% / bio-EVA 70.6%,
- PHAs NHK* - bio-silica 21.7% / bio-EVA 78.3%,
- PHAs NHK** - bio-silica 37.5% / bio-EVA 62.5%.

This variation of compositions allows investigation of the impact of filler type and content on the environmental performance of the resulting foam while considering its mechanical properties and structural stability. For comparison purpose, compounds commonly used in the footwear industry were selected as reference materials: i) PUR — the standard material used for midsoles and insoles due to its combination of elasticity and dimensional stability; ii) EVA — a lightweight and resilient material, widely applied in athletic and everyday footwear; iii) Foamed Natural Rubber (NR) — often used in sustainable footwear concepts due to its softness and abrasion resistance; and iv) Foamed TPU — a premium elastic material valued for its durability and energy return. To enable a comprehensive environmental comparison, several bio-based alternatives were also included: i) PLA Foam — a rigid, thermoformable foam based on polylactic acid; ii) PBS Foam — a semi-flexible foam with moderate resilience based on PBS; iii) TPS Foam — a fully biodegradable foam derived from thermoplastic starch, suitable for lightweight cushioning. Furthermore, partner IWV developed laboratory samples of crosslinked PUR foams based on a-P3HB provided by partner HSKL. All samples went comparative assessment to develop a comprehensive understanding of both laboratory-scale and industrial PHA applications in footwear foams. This enables a detailed analysis of the potential advantages and limitations of bio-based materials in contrast to conventional ones. With a broad range of benchmark materials — both petrochemical and bio-based — the evaluation covers both functional and environmental aspects relevant to footwear manufacturing. Literature data on PUR, EVA, NR, TPU, PLA, PBS, and TPS serve as key reference points for evaluating the innovation potential of new PHA-based materials.

The LCA results are presented in Figure 17 based on 1 kg of finished product. Direct replacement of the mineral filler by a bio-based one in foam formulations based on both PHA.A.2.3.1.4 developed in **W2BC** and industrial PHA (samples PHA HN/PHA HN* and PHA IN/PHA IN*, respectively) resulted in minimal reduction of CO_2-emission, whereas energy consumption remained the same. Obvious improvement of GWP100 value could be achieved by varying filler type and content (systems PHA HNK/PHA HNK*/PHA HNK**). However, it was accompanied by some increase of NREU indicator. Nevertheless, it can be stressed that foam PHA HNK** resulted in the most beneficial LCA results. Considering the reduction of GWP100 factor with only slight increase of energy consumption for foams based on PHA.A.2.3.1.4 and PHA.K.3.3.1.4 compared to those based on a commercial PHA, it can be concluded that **W2BC**-foams based on these materials can be considered as more sustainable alternatives. Comparison of LCA results for these foams with literature data for various reference foams shows that they could also be considered as more sustainable alternatives or at least have potential to be used as components in other foams for improvement of their sustainability, especially considering obviously lower NREU values characteristic for foams developed and investigated in **W2BC**.



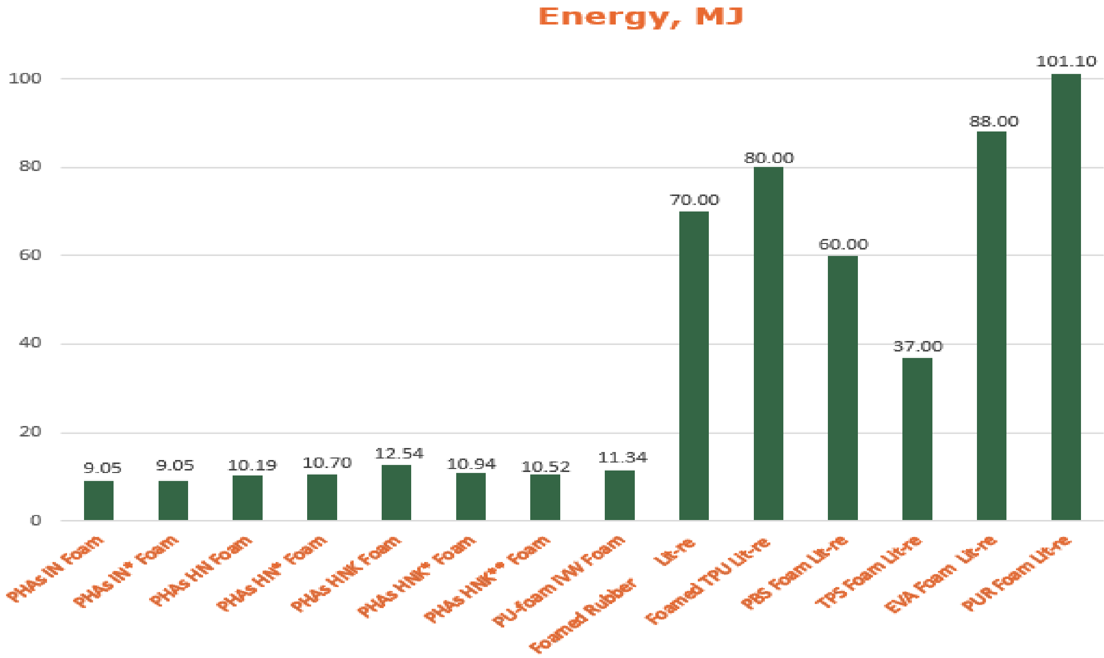


Figure 17 LCA results for the PHA- and PUR-based foam production processes.

Comparison of a-P3HB-based PUR-foam developed by partner IVW with the literature data for common PUR-foams for shoe applications also clearly indicates the environmental benefits of new foam in terms of both GWP100 and NREU indicators.

Production of PHA-Based Fibres via Wet-Spinning Method

As part of the development of bio-based fibre solutions within the **W2BC** project, three different PHA samples were tested at small laboratory-scale by partner CITEVE using the same wet-spinning method. The objective was to assess and compare the fibre formation efficiency of an industrial-grade PHBHHx (Process 1) and two lab-scale samples provided by HSKL: PHA.A.2.3.1.1 (Process 2) and PHA.C.3.3.1.4 (Process 3).

For comparison, existing LCA results for PHA-fibres produced via electrospinning and wet-spinning were considered focusing specifically on processes involving chloroform and ethanol.

Estimation of Spinning Time and Energy Consumption for PHA-Fibres

As part of the study, the spinning duration for each fibre sample was independently calculated based on productivity data provided by partner CITEVE. The assumed productivity rate was 0.0105×10^{-3} kg/min, which enabled the calculation of processing time for each sample using the following formula:

$$t_{Spinning} = \frac{m_{Product}}{P},$$

where P is the process productivity rate.

Based on the calculated time and the power rating of the syringe pump (0.024 kW), the energy consumption for each spinning process was also estimated.

Summary of results:

- **Process 1 – PHBHHx-fibres:**
  Product mass: 0.15×10^{-3} kg
  Spinning time: 14.29 minutes
  Energy consumption: 0.00572 kWh
- **Process 2 – PHA.A.2.3.1.1-fibres:**
  Product mass: 0.105×10^{-3} kg
  Spinning time: 10.00 minutes
  Energy consumption: 0.00400 kWh
- **Process 3 – PHA.C.3.3.1.4-fibres:**
  Product mass: 0.03×10^{-3} kg
  Spinning time: 2.86 minutes
  Energy consumption: 0.00114 kWh

Reference Values for Comparison

For comparison, reference data on wet-spinning processes using commercial polymers such as PHA, PLA, and PBS were selected. The literature describes several process variants based on different solvent systems, summarised below as benchmark scenarios:

- Scenario 1: PHA – dichloromethane
- Scenario 2: PLA, PBS, PHA – formic acid / ethanol
- Scenario 3: PLA – acetone / ethanol

These examples serve as a basis for technical and environmental benchmarking against the current study, in which chloroform and ethanol were used. The LCA results for these processes are presented in Figure 18, normalised to 1 kg of finished product. This functional unit was selected for better comparability with the literature data and because partner CITEVE confirmed the scalability of the spinning process to this level with at least the same productivity rate, when the same equipment is used.

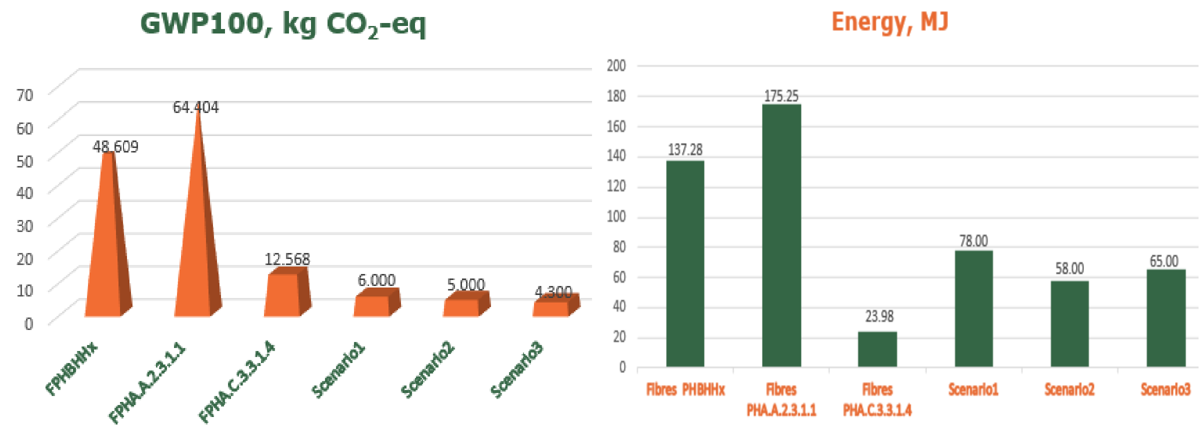


Figure 18 LCA results for the wet-spinning production process of CITEVE and selected benchmark Scenarios 1-3.

Unfortunately, high values of both GWP100 and NREU have been obtained for all three wet-spinning systems processed by partner CITEVE, especially for fibres based on PHA.A.2.3.1.1 and commercial PHBHHx, whereas only fibres made of PHA.C.3.3.1.4 could be considered as promising because of obviously lower energy consumption, even compared to benchmark scenarios. However, it must be considered that direct transfer of small lab-scale productivity rate to scale-up scenario is the main factor causing high sustainability indicators obtained. Productivity rate in the fibre spinning is a critical parameter that directly affects processing time, equipment efficiency, and overall energy consumption. Higher productivity allows for faster production of the final product, which in turn reduces electricity usage and operational costs. In the context of LCA, this has a direct impact on indicators such as NREU and GWP100. The comparison of PHA-samples in this study shows that even under identical conditions, differences in product mass, given a fixed productivity rate, determine the energy intensity per unit of product, making productivity a significant factor in the overall sustainability assessment of the process. Therefore, obvious reduction of both sustainability indicators is expected by industrialisation of the wet-spinning process developed by partner CITEVE.

Application of Water-Based Dispersion Coatings on Textile Substrates

As part of a laboratory study within the **W2BC** project, partner CITEVE developed two processes, i.e., knife and spray coating, for creating functional biodegradable PHA-layers on textile material, i.e., polyester (PES) fabric produced by partner RIOPELE, using aqueous polymer dispersions based on an industrial-grade PHBHHx sample for knife coating (PHBHHx-coated textile) and an alternative PHA-formulation developed in frame of **W2BC** (formulation PHB.E.0) for spray application. The following process steps were used for both coating methods:

- Knife coating: Mixing the polymer with water (stirrer) → Ultrasonic treatment to stabilise the dispersion (sonicator) → Addition of thickener and further mixing (overhead stirrer) → Application of the coating onto textile via knife coating (labcoater) → Drying/thermal fixation (labcoater) → Further film formation (hot-press)
- Spray coating: Mixing the polymer with water and additives (stirrer) → Ultrasonic treatment (sonicator) → Spraying onto fabric surface (spray equipment) → Drying/thermal fixation (dryer)

These methods enable the formation of a thin and uniform coatings on a textile substrate without use of organic solvents. While the two approaches differ in application method, coating thickness, and material losses, both share a common goal: creating a functional surface layer on textile substrates. To support the environmental evaluation, averaged literature LCA values were used from similar knife coating processes involving Poly(3-hydroxybutyrate-co-hydroxyalkanoate) (PHBH), Poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV), and PLA on paper substrates. Although the substrate differs (paper *vs.* textile), the process stages, the overall energy demand, use of water as a solvent, the nature of the biopolymer materials, and the fundamental application method remain similar. This allows a valid approximation of the environmental impacts making these reference data suitable for indicative comparison and assessment within the current study, within the context of a comparative LCA. The related LCA results are shown in Figure 19, based on 1 kg of finished product.

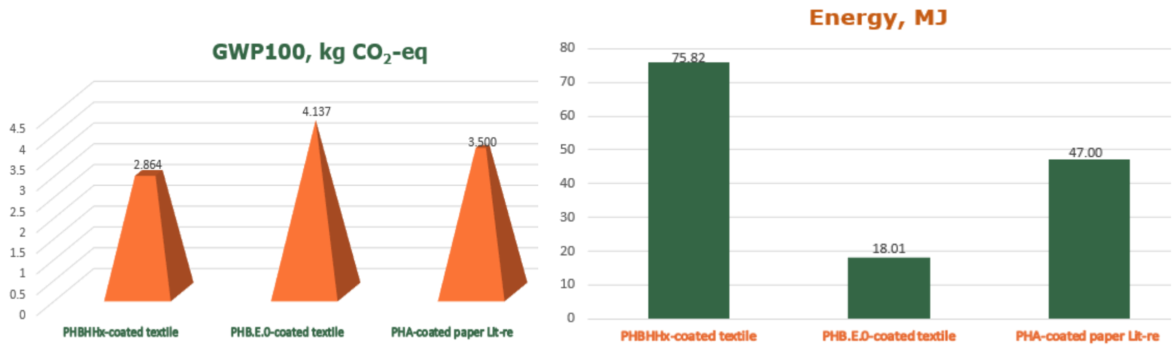


Figure 19 LCA results for the knife and spray coated textiles vs. knife-coated paper as reference.

Despite one additional formulation step in the knife coating process chain compared to spray coating process chain, lower GWP100 value was obtained for knife coating. However, this was accompanied by obviously higher energy consumption compared to the spray coating application. Higher energy consumption for knife coating process chain was also observed compared to the literature LCA-data for PHA-coated paper while the environmental impact (GWP100-value) of the reference was higher. This result is mostly related to the creation of a thicker coating layer by knife coating, requiring longer drying times. Therefore, there is potential for optimisation of the sustainability of the knife coating process chain by reduction of coating thickness and related drying time. Despite higher environmental impact of spray coating process chain compared to that utilizing knife coating, obviously lower energy consumption was determined for it. This makes spray coating application more beneficial.

Printing processes with bio-based inks

It is worth noting that printing processes have traditionally been associated with significant emissions of pollutants, including volatile organic compounds and other toxic components that can negatively impact air quality and the environment. In addition, the printing process requires significant water and energy consumption and generates waste that may require special disposal. The use of bio-ink, as in the **W2BC** project, can help reduce environmental impact by using safer and more sustainable renewable materials.

As part of the **W2BC** project (WPs 1-2), partner CITEVE has carried out printing tests using bio-ink developed in WP1 using a bio-pigment developed by partner PILI. Specifically, samples of three bio-inks differing mostly in binder and additive components were applied under the following process scenarios to 100% natural textile:

- Scenario 1 (Synthetic binder in textile pre-treatment, ink with synthetic binder): Pre-treatment (Foulard) → Drying (dryer) → Digital printing (Chromojet TableTop printer) → Drying (dryer) → Fixing(dryer)
- Scenario 2 (1% biopolymer binder in textile pre-treatment, ink with synthetic but biodegradable binder): Pre-treatment (Foulard) → Drying (dryer) → Digital printing (Chromojet TableTop printer) → Drying (dryer) → Fixing (dryer) → Washing (domestic washing machine)
- Scenario 3 (1% biopolymer binder in textile pre-treatment, ink with just pigment in water - no binder): Pre-treatment (Foulard) → Drying (dryer) → Digital printing (Chromojet TableTop printer) → Drying (dryer) → Fixing (dryer) → Washing (domestic washing machine)

These scenarios allow a comprehensive evaluation of the performance of bio-ink printed on a natural textile, considering differences in post-treatment processes such as fixing (Scenario 1) and fixing followed by washing (Scenarios 2 and 3), whereas three different binder scenarios were tested in these trials to assess their impact on adhesion and quality of bio-ink. It is important to note that addition of 1% biopolymer additive in Scenarios 2 and 3 was used to increase the durability and performance of the bio-ink.

As part of further research, using data for optimized processes provided by partner PILI (who independently calculated the GWP100 values), three additional printing scenarios were modelled using the updated environmental performance indicators. These new variants are designated as

Scenario 1*, Scenario 2*, Scenario 3*, where the technological processes remained unchanged (see Scenarios 1-3), but the bio-ink impact parameters were adjusted based on the new data provided.

For comparison, a reference GWP100 value for petroleum-based indigo dye was taken from scientific literature. Based on this data, three more printing scenarios were modelled, replicating the same process steps as in the previous cases, but substituting the bio-based indigo with petroleum-based one in the ink formulations. These scenarios are referred to as Scenario 1**, Scenario 2**, and Scenario 3**. The LCA results for abovementioned scenarios are presented in Figure 20, normalised to 1 kg of finished product.

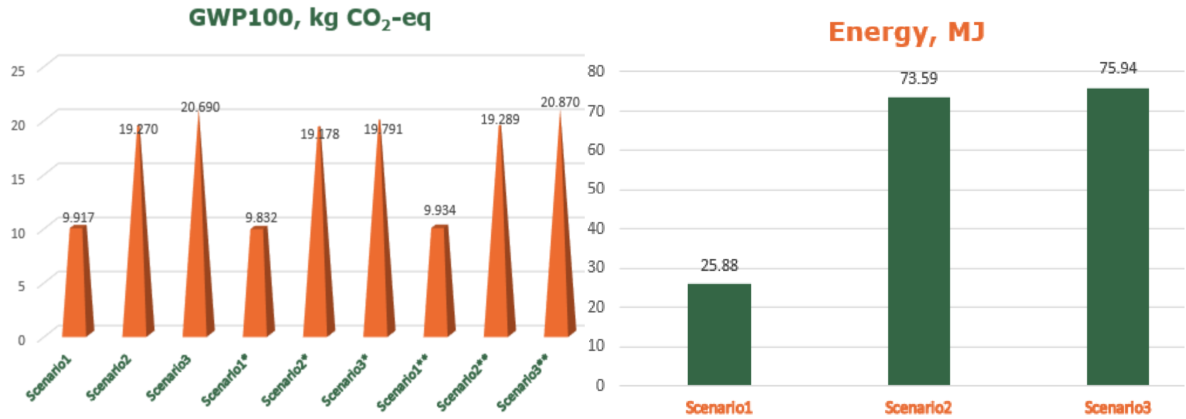


Figure 20 LCA results for the different inkjet printing process scenarios.

Despite the replacement of the synthetic binder in the textile pre-treatment (Scenario 1) with a bio-based one (Scenarios 2 and 3) provided some environmental benefits, higher LCA-indicators were obtained for optimised formulation due to the necessary additional post-treatment step, i.e., washing. Unfortunately, removal of the binder and other additives within the ink (Scenario 3) didn't contribute positively to the LCA-indicators because longer drying of printed bio-ink was required. This resulted in some further increase of both indicators. As expected, process optimisation related to the production of bio-based indigo didn't improve the environmental impact of bio-ink printing processes drastically (compare Scenarios 1-3 with Scenarios 1*-3*). Nevertheless, GWP100 values of all printing processes with bio-inks containing bio-based Indigo remained slightly lower than those for models with petroleum-based Indigo. Considering the small amount of Indigo in the inks and its marginal influence on the sustainability indicators of the inkjet printing processes, this is a clear indicator that bio-based indigo is more sustainable compared to the synthetic one.

Formulation of Improved Indigo-Based Bio-Ink for Digital Printing

As part of the development of sustainable printing technologies within the **W2BC** project, the bio-ink formulation based on the bio-derived indigo pigment produced by PILI was improved, namely in terms of dispersibility. The formulation process comprised several sequential steps of preparation and treatment aimed at ensuring stable dispersion, printability, and durability of the final product:

- Indigo pre-dispersion (ball mill) → Mixing with water → Sonication (ultrasound probe) → Ink formulation (addition and compounding of remaining components) → Ultrasound treatment (water bath) → Filtration (vacuum pump)

This process represents a structured, energy-intensive yet scalable approach to the formulation of bio-based inks for sustainable applications in digital textile printing. Based on 1 kg of finished product as functional unit, quite low GWP100 of 2.651 kgCO_2-eq but high energy consumption (NREU = 523.566 MJ) were estimated for it.

Chemical Recycling of PHA-based materials

As initial stage, partner GR3N performed industrial-scale recycling trials involving the commercial PHA sample from Go!PHA. This material was subjected to three chemical recycling technologies established for polyesters:

- Thermolytic Distillation (TD)
- Alkaline Hydrolysis (AH)
- Catalysed Methanolysis (CM)

Each method was designed to optimise the depolymerisation of PHA, enabling the recovery and potential reuse of its components in new production cycles. It is important to highlight that these processes also involve the recovery and reuse of solvents, which significantly contribute to reducing the environmental impact of the recycling systems.

Furthermore, several additional recycling scenarios involving various types of PHA-based materials also have been modelled and assessed:

- PHA.K Biopolymer (Partner HSKL)
- Flexible PHA/PLA-Packaging Film (Partner PROPAGROUP)
- PHA/EVA-Foam for Footwear Applications (Partner NORA)
- PHA/MPs Composite Rigid Packaging (Partner: UDC)

It is noteworthy that depending on the recycling object and method different main depolymerisation products could be conducted, like various alkoxybutyrates and hydroxybutyrates, crotonic, hydroxy- and alkoxybutyric acids, respective sodium salts, etc.

The obtained data allow a comparative analysis of the environmental performance between the recycling of PHA materials developed within the **W2BC** project and industrial-grade samples such as Go!PHA. At the same time, the final evaluation also focused on the potential for further reuse of the recycled material, which was the key objective of this part of the study. The LCA results for all abovementioned processes are presented in Figure 21, normalised to 1 kg of finished product.

Nr.	Polymer	Recycling method	GWP100, kg CO_2-eq	Energy, MJ
1	Go!PHA	TD	8.068	44.90
2	Go!PHA	AH	3.289	94.06
3	Go!PHA	CM	8.644	42.06
4	PHA.K.3.3.1.4	AH	11.478	95.30
5	PHA.K.3.3.1.4	CM	2.191	64.01
6	PHA.K.3.3.1.4	AH+acid	3.575	347.98
7	PHAS Propagrup (PHA.K)	CM	2.017	70.88
8	PHAs UDC rigid packaging	CM	3.364	236.15
9	PHAS NORA (PHA.K)	CM	9.379	117.58

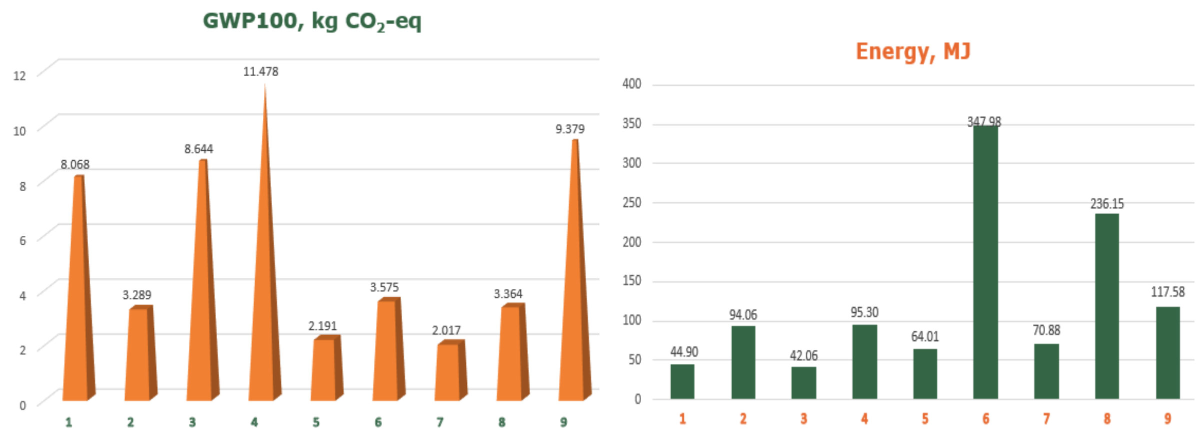


Figure 21 LCA results of the chemical recycling processes for different PHA-based materials.

The results obtained for the three different chemical recycling methods of commercial Go!PHA sample indicate that environmental impact of AH is lower compared to TD and CM resulting in quite high GWP100-values. However, lower energy consumption is characteristic for these two methods compared to AH. In contrary, CM of sample PHA.K.3.3.1.4 resulted in obviously better LCA-indicators compared to AH. The environmental impact of AH of PHA.K.3.3.1.4 was obviously improved by implementation of acidic post-treatment converting not only the depolymerisation products in more valuable ones but also reusable solvent as byproduct to more sustainable one. However, extremely high energy consumption was required for this. Based on these results, CM was selected as the most promising chemical recycling technology for selected PHA-based multicomponent products, i.e., PHA.K-based film and foam, and PHA-based rigid plastic packaging, whereas the best LCA result was obtained in case of chemical recycling of PHA.K-based film.

Chemical Repolymerisation of Recycled PHA-Based Materials

The final stage of the LCA modelling within the **W2BC** project involved simulation of laboratory-scale chemical repolymerisation processes, based on the previously described PHA recycling scenarios carried out via CM. The objective was to evaluate the feasibility of the reuse of recycled raw materials for the formulation of new PHA-based blends, thus supporting the potential for establishing closed-loop systems. Five material streams, obtained from earlier recycling trials, were included in this analysis:

GO!PHA
- Repolymerisation: chemical (HSKL WP1)

Rigid packaging (PHA/microparticles) – UDC
- Repolymerisation: chemical (HSKL WP1)

PHA.K (HSKL)
- Repolymerisation: chemical (HSKL WP1)

Flexible packaging film (PHA/PLA) – PROPAGROUP
- Repolymerisation: chemical (HSKL WP1)

Foam (PHA/EVA/Silica/etc.) – NORA
- Repolymerisation: chemical (HSKL WP1)

For each case, up to 40% of recycled material was repolymerised and reintroduced in the selected formulation of a PHA-blend, a composite blend designed for further processing into new materials or products. This approach enables a comprehensive assessment of both the technical feasibility and environmental potential of reuse of PHA-based materials.

The results provide a solid foundation for modelling circular production systems and highlight the pivotal role of chemical repolymerization in establishing closed-loop, sustainable biopolymer VCs. To broaden the scope of environmental evaluation within the context of a circular economy, the study also incorporates reference data from LCA-analyses covering the reuse of various polymers, including recycling of PHB, PHB-Film, and PUR-Foam. The integration of such literature-based sources allows a comparative assessment of the environmental performance of biopolymer recycling *vs.* conventional approaches, helping to identify their respective advantages and limitations while strengthening the rationale for the adoption of innovative technologies in sustainable industrial practices.

The LCA results for all abovementioned processes are presented in Figure 22, normalised to 1 kg of finished product.

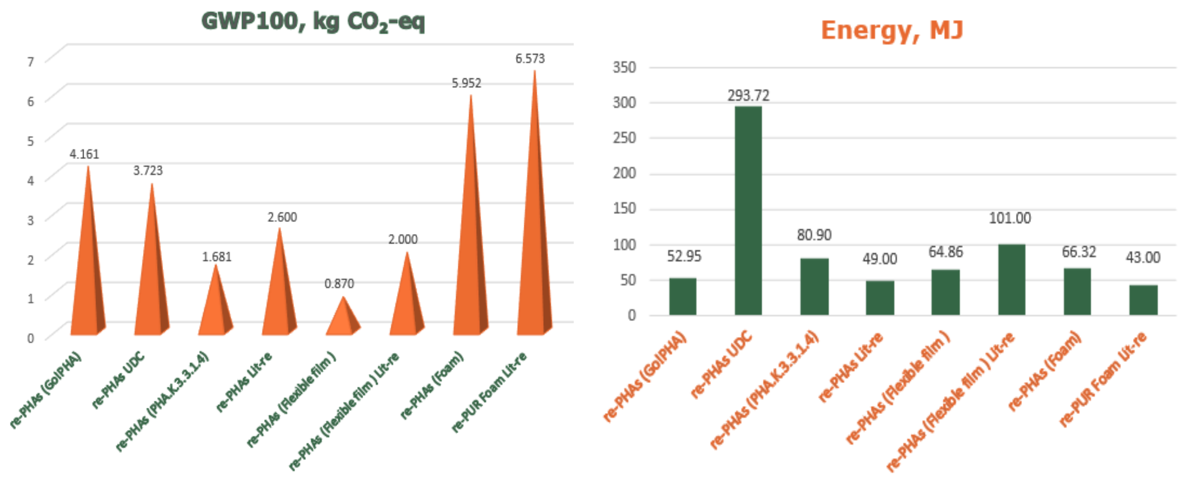


Figure 22 LCA results for repolymerisation processes in comparison to selected literature data.

In all cases, except reuse of repolymerised recyclates from Go!PHA and PHA-based rigid plastic, the GWP100-values lower than those of respective literature references have been achieved. However, only in the case of PHA-based flexible film lower energy consumption compared to the reference was possible. All other systems resulted in higher NREU-values, especially in the case of the rigid plastic. The most beneficial LCA results have been obtained in the case of reuse of repolymerised recyclates in the production of PHA.K.3.3.1.4 blend and especially PHA-based film.

2.2.5. Interpretation and General Conclusions of the LCA

Interpretation and general conclusions on the LCA have been combined into a single section, as the assessment covers a limited number of impact categories. The focus is exclusively on energy consumption and CO_2-equivalent emissions (i.e., the Climate Change / Global Warming Potential category), which allows the LCA structure to be simplified without compromising analytical depth.

Process Optimization Based on Early LCA-Results

The LCA results obtained at early stages (PMA, PGA, a-P3HB(S*), a-P3HB(L**), a-P3HB-ROP, a-P3HB(R)*) served as a key reference point for improving laboratory and semi-industrial processes. In particular, the LCA results made it possible to identify hot spots — stages with the highest environmental impact — and formulate recommendations, some of which were partially implemented in the further development of materials (PHA.A.2.3.1.4, PHA.A.2.3.1.1, PHA.K.3.3.1.4, PHA.C.3.3.1.4).

During the testing of chemical synthesis routes for PHAs (HSKL), a significant variability in environmental performance was recorded — ranging from relevant to critically high values. This prompted adjustments to the processes, including the reduction of energy consumption and the substitution of certain chemical components. As a result, materials with improved quality and environmental indicators have been obtained.

Optimized Chains with the Most Consistent Results

The most stable results throughout all stages were observed in the compatible chains between HSKL and PROPAGROUP, specifically in the PHAs, PHAs*, and PHAsK variants. These successful results were attributed to the continuous improvement of the formulations and processing conditions as well as to the equipment allowing high stability and reproducibility of processes, which minimized deviations in production conditions.

Particular attention should be given to the PHAsK variant, which, during recycling, resulted in two products: one was accepted for further repolymerization modelling, while the other was excluded from calculations in line with LCA methodology principles. This approach avoided the inclusion of irrelevant by-products in the carbon footprint analysis and preserved the integrity of scenario comparisons.

Bio-PHB and Identified Hot Spots

Similar recommendations were formulated for the development of PHBbio processes. However, in this case, most proposals, particularly those related to reducing energy consumption could not be implemented in the timeframe of the project. As a result, these processes became pronounced hot spots, leading to elevated environmental impact values in all scenarios where this material was used as feedstock for bioproducts within the project framework.

Critical Stages and Technical Limitations

High energy consumption was also detected in processes for MPB and rigid plastic production. An additional factor intensifying the environmental burden was the geographic location of production facilities. For example, processes conducted in Germany showed the highest carbon footprint due to the country's specific energy mix.

Textile-related Process Chains

In the wet-spinning processes, the reuse of solvents was proposed to reduce the environmental load.

The formulation of indigo-based bio-ink for digital printing proved particularly energy-intensive, and no literature-based reference data are currently available for comparison.

In the test processes of printing using different bio-based inks and pre-treatments, significant hot spots included excessive electricity and water consumption. A comparison of various ink formulations across investigated scenarios revealed no substantial differences in environmental impact, while the bio-based pre-treatment results in higher environmental impact, comparing with the synthetic one, due to the additional washing step. As future work, it would be interesting to compare these processes in higher production scale, as the impact of the washing step would dilute per kg of printed textile.

Scaling and Data Reliability Constraints

When scaling up processes to the 1 kg level, significant challenges were encountered in assessing energy consumption due to the lack of precise equipment parameters. Processes producing 1–5 kg of product yield relatively reliable results, while those with smaller-scale formulations demonstrate considerably inflated indicators. This is due to the inability to accurately calculate the scaling coefficient for energy consumption, which is especially critical in laboratory conditions where partners often lack access to complete technical data.

Outcomes and Limitations of Chemical Recycling and Reuse of Recyclates

Following the implementation of initial chemical recycling scenarios, a well-considered decision was made to continue using the most sustainable approach, i.e., the CM method was selected as the most relevant for most chains.

Key hot spots identified during the repolymerization of samples obtained after chemical recycling include:

- Not very high substitution yield (i.e., 40%) — only 0.4 kg of usable secondary polymer could be recovered per 1 kg of waste.
- High energy consumption — chemical recycling requires 2.5–4 times more energy than mechanical recycling. This is due to high-temperature processes, the use of solvents and catalysts, and the incomplete recovery and reuse of solvents, requiring the addition of new chemicals and increasing the overall environmental load.

These parameters can be considered by future optimisations of the chemical recycling processes.

2.2.5.1. Main environmental achievements

KPI improvement (%) PHA

PHA systems (based on literature references):

- PHA.A.2.3.1.4 demonstrated a 32.66% reduction in GWP100 and a 83.95% decrease in energy consumption.
- PHA.A.2.3.1.1 achieved a 69.74% improvement in GWP100 and 84.36% lower energy usage.
- PHA.K.3.3.1.4 proved to be the most sustainable option, with a 76.90% reduction in GWP100 and 90.57% energy efficiency.
- PHA.C.3.3.1.4 delivered a 70.74% GWP100 improvement, accompanied by an impressive 96.91% decrease in energy demand.

General Conclusions:

- All listed samples achieved more than 30% reduction in climate impact compared to reference alternatives, highlighting significant progress in carbon footprint reduction.
- Energy efficiency levels exceeding 80% indicate a high degree of process optimization across production chains.
- The highest environmental achievements were recorded for PHA.C.3.3.1.4 and PHA.K.3.3.1.4, which can be considered benchmark options in terms of sustainable development.

These results confirm the success of the technical optimization strategies implemented within **W2BC** and validate the viability of PHA-based approaches for broader industrial integration in line with circular economy principles.

KPI improvement (%) Flexible film

PHA-based biofilm formulations compared to literature-based reference data for conventional PHB biofilms:

- PHAs (50%/50% LDPE): achieved a 31.69% reduction in GWP100 and 22.90% decrease in energy consumption.
- PHAs* (70%/30% LDPE): delivered a 23.08% improvement in GWP100 and 25.30% energy savings.
- PHAsK (70%/30% PLA): showed the best overall performance, with a 44.21% reduction in GWP100 and 24.15% lower energy demand.

General Conclusions:

- All tested formulations demonstrated a significant reduction in carbon footprint, highlighting the potential of PHA-based films in sustainable packaging applications.
- PHAsK, formulated with PLA, delivered the most favourable environmental outcomes, particularly in terms of GWP100, making it a strong candidate for further development and upscaling.
- The results confirm the viability of partially replacing petrochemical-based polymers with bio-based alternatives in the flexible packaging sector, supporting the transition to more sustainable material systems.

These findings provide solid evidence of the environmental advantages of bio-based flexible films and offer a foundation for industrial integration aligned with circular economy principles.

KPI improvement (%) EVA Foam

Evaluated PHA foam variants, compared with conventional petrochemical EVA foams):

- PHAs HN: GWP100 reduction of 23.00%, energy savings of 88.42%.
- PHAs HN*: GWP100 reduction of 25.00%, energy efficiency at 87.84%.
- PHAs HNK: GWP100 improvement of 48.00%, energy reduction of 85.75%.
- PHAs HNK*: GWP100 improvement of 42.39%, energy efficiency at 87.57%.

- PHAs HNK**: best results with 53.28% lower GWP100 and 88.04% energy reduction.

General Conclusions:

- All studied PHA systems demonstrated substantial reductions in climate impact (GWP100), confirming their strong potential to reduce the carbon footprint compared to conventional EVA foams.
- Energy efficiency improvements were consistently high — above 85% across all samples, indicating significant process-level energy optimization.
- The PHAs HNK** variant showed the most outstanding environmental performance, combining the highest climate benefit with excellent energy efficiency.

These findings reinforce the suitability of PHA-derived materials for flexible foam applications and highlight their relevance as a sustainable alternative in the context of circular bioeconomy development and industrial-scale innovation deployment.

KPI improvement (%) Wet-Spinning of PHA Fibres

In the framework of the LCA evaluation, the sample PHA.C.3.3.1.4 (PHBHHx-based biopolymer) demonstrated highly favourable environmental performance when compared to conventional reference materials.

Environmental indicators:

- Climate impact (GWP100) reduction: 74.17%
- Energy demand reduction: 82.56%

General Conclusions:

- The PHBHHx-based variant PHA.C.3.3.1.4 exhibited one of the highest improvements among all tested PHA systems, confirming its strong environmental advantages.
- The combination of significant GWP reduction and high energy efficiency marks this material as a high-potential candidate for industrial applications focused on sustainability and decarbonization.
- These results clearly position PHBHHx-based solutions as leading alternatives in the transition to bio-based, low-carbon production chains aligned with principles of circular economy.

KPI improvement (%) Coating of Textile

Knife Coating (PHBHHx) (compared to conventional reference systems):

- Climate impact reduction (GWP100): 18.70%
- This reflects a meaningful decrease in CO_2-equivalent emissions, indicating potential for replacing traditional coatings with bio-based alternatives.

Spray Coating (PHB.E.0) (compared to conventional reference systems):

- Energy consumption reduction: 61.68%
- Highlights significant energy savings and improved efficiency through the spray coating technique.

General Conclusions:

- Both coating technologies (i.e., knife and spray coating) show environmentally beneficial performance depending on the impact category (climate or energy).
- The PHB.E.0-based spray coating exhibits superior energy efficiency, making it particularly suitable for scalable production.
- These results confirm the feasibility of PHA-derived coatings for sustainable textile solutions and support their broader integration into eco-conscious manufacturing chains.

KPI improvement (%) Chemical Repolymerization of Recycled PHA-Based Materials

Re-PHB (PHA.K.3.3.1.4):

- Compared to Go!PHA sample: GWP100 reduction of 59.59%
- Based on literature references: GWP100 reduction of 35.35%
- These results confirm the superiority of **W2BC**-optimized processes over conventional reference scenarios, particularly in terms of carbon footprint reduction.

Re-PHB (Foam application):

- GWP100 reduction: 30.16%
- Energy savings: 37.77%
- This reflects a moderate environmental benefit with potential for further optimization in foam recycling chains.

Re-PHB (Flexible film):

- GWP100 reduction: 56.50%
- Energy savings: 35.78%
- This configuration stands out as one of the most effective pathways for re-PHB reuse, with a well-balanced sustainability profile.

General Conclusions:

- The repolymerized PHA-systems outperformed literature-based references validating the effectiveness of the **W2BC**-specific processing chain.
- Flexible film applications demonstrated strong potential for sustainable reuse combining high climate impact reduction with solid energy efficiency.
- These results emphasize the importance of use of project-specific LCA data over generic literature sources to ensure accuracy in environmental assessment and support evidence-based decision-making.

2.3. Life Cycle Costing (LCC)

In the **W2BC** project, one of the key tasks was to calculate the LCC for the new PHA-based materials. The LCC methodology allows the estimation of costs across all stages of a material's life cycle, from raw material extraction to disposal. This provides an understanding not only of the direct financial costs but also of the potential environmental and economic impacts at various stages of the material's use.

2.3.1. Data collection

To conduct the LCC analysis, a data collection template has been developed (Figure 23), which includes all necessary categories of costs.

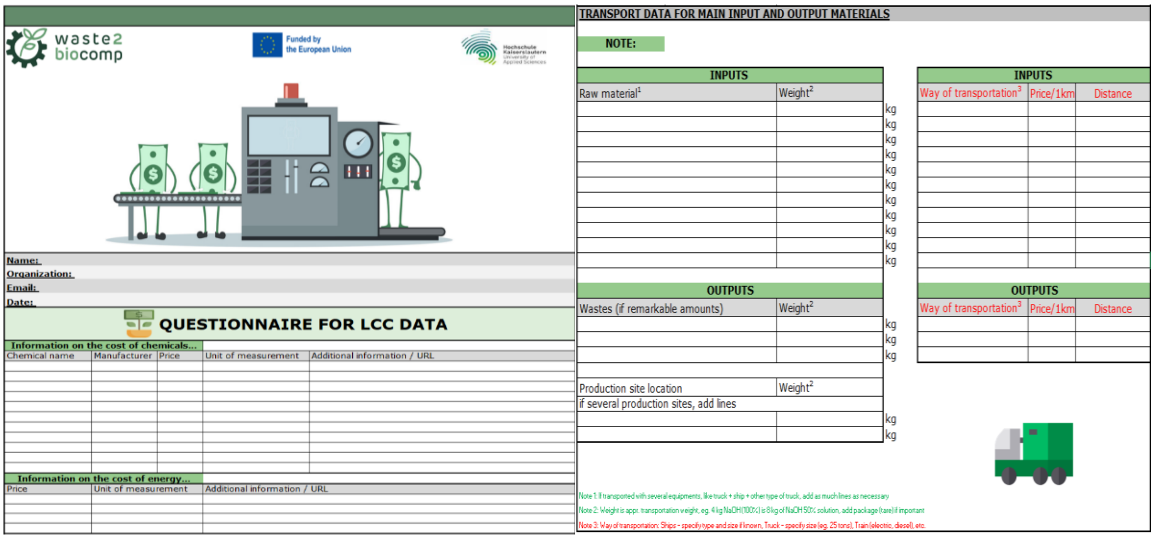


Figure 23 Template for LCC data collection.

The template helps to structure the information related to different stages of the PHA life cycle. In laboratory conditions, it is important to focus on several key data points to ensure accurate assessment:

- Raw Material Costs**:** Data on the amount and cost of raw materials used for polyhydroxybutyrate (PHB) synthesis.
- Energy Consumption**:** Estimates of the energy required at different stages of the process, such as fermentation or material processing.
- Production Time**:** An important metric for evaluating labour and resource costs at each stage.
- Emissions and Waste: Assessing the amount of waste and emissions generated, which could influence future disposal or recycling costs.

2.3.2. LCC results

2.3.2.1. Synthesis of a-P3HB via polycondensation and a-PHB based PHAs

The LCC-results for a-PHB synthesised via polycondensation and selected related PHA-blends are presented in Table 1. The respective economic feasibility, potential for cost reduction, and environmental aspects are briefly outlined below.

Table 1 LCC for a-PHB obtained via polycondensation and related selected blends

LCC a-P3HB

Cost items	Costs [EUR]
Material Costs	17.68
Energy Costs	0.79
Total Costs	**1 kg [EUR]**
Process a-P3HB	18.47

LCC PHA.C.3.3.1.4

Cost items	Costs [EUR]
Material Costs	17.72
Energy Costs	0.35
Total Costs	**1 kg [EUR]**
Process PHA.C.3.3.1.4	18.07

LCC PHA.K.3.3.1.4

Cost items	Costs [EUR]
Material Costs	12.88
Energy Costs	0.27
Total Costs	**1 kg [EUR]**
Process PHA.K.3.3.1.4	13.15

- Economic Feasibility: In laboratory conditions, the production of a-PHB can be quite expensive due to the high precision required in the synthesis processes, as well as significant energy and material costs. However, at an industrial scale, these costs can be significantly reduced through process optimization, automation, and more efficient resource utilization.
- Potential for Cost Reduction: With the growing demand for biodegradable materials, PHAs, especially in packaging, textile, and footwear industries, hold significant economic potential. However, industrial production of PHAs still remains costly due to limited production volumes and technological challenges. Expanding production scale can help reduce costs substantially.
- Environmental Aspects: The use of renewable energy sources and a reduction in CO_2 emissions could make the process eco-friendlier. Since PHAs are biodegradable, they are particularly attractive to markets with stringent environmental requirements, potentially increasing demand and improving production economics.

The economic feasibility of PHA production depends on scaling up and optimizing technological processes. While laboratory methods are expensive due to material and energy costs, further advancements in both chemical and microbiological methods and the growing demand for biodegradable materials could make industrial production more economically viable in the future.

2.3.2.2. Synthesis of a-PHB via ROP

Table 2 LCC for a-PHB obtained via ROP

LCC a-PHB(ROP)

Cost items	Costs [EUR]
Material Costs	1506.25
Energy Costs	1.88
Total Costs	**1 kg [EUR]**
Process a-PHB(ROP)	1508.13

- Economic Feasibility: This method incurs high energy and material costs, making it less economical for large-scale production (Table 2). The laboratory cost of producing 1 kg of a-PHB via ROP is €1,508.13, which is quite high for industrial-scale production. This is due to significant energy consumption, material costs, and the complexity of the polymerization process that requires specific reagents and precise temperature control.
- Potential for Cost Reduction: Similar to chemical synthesis, the economic efficiency of the ROP method will improve with increased production scale. The volume increase will allow unit cost reduction through economies of scale, but significant process optimization and effective resource management are essential.
- Environmental Aspects: New ways to reduce energy and material costs could make this method more economically viable from both material and ecological standpoints.

The ROP method for a-PHB synthesis is currently less economically viable due to high unit costs. However, with technological advancements and scaling, costs could decrease, and the growing market for biodegradable materials offers future potential for increased demand for PHB.

2.3.2.3. Pilot production of flexible packaging films

This part evaluates the economic viability of pilot production of bio-based materials for flexible packaging, considering two primary scenarios: PHAs and PHAs*. The analysis includes material and energy costs. The evaluation is based on laboratory data from project partners; however, cost adjustments will be necessary as the production scale shifts to commercial manufacturing. The respective results are shown in Table 3.

Table 3 LCC for PHA-based films

LCC PHAs

Cost items	Costs [EUR]
Material Costs	13.91
Energy Costs	3.53
Total Costs	**1 kg [EUR]**
Process PHAs	17.44

LCC PHAs*

Cost items	Costs [EUR]
Material Costs	14.43
Energy Costs	3.64
Total Costs	**1 kg [EUR]**
Process PHAs*	18.07

LCC PHAsK

Cost items	Costs [EUR]
Material Costs	17.73
Energy Costs	1.82
Total Costs	**1 kg [EUR]**
Process PHAs	19.55

- Economic Feasibility: The production of bio-based materials for flexible packaging demonstrates economic viability, as the main costs are associated with bio-based polymers, stabilizers, and additives, as well as energy costs, which are low. This reflects the energy efficiency of the process, positively impacting the economic performance.
- Potential for Cost Reduction: There is potential for cost reduction using alternative bio-material sources or by production scaling up. Optimization of technological processes and the implementation of automation can also reduce labour and processing costs. These changes will significantly lower costs when the production moves toward commercialization.
- Environmental Aspects: The production process of bio-based materials is sustainable, as it meets modern demands for environmentally friendly solutions. This reduces waste disposal costs, as the materials are biodegradable, and lessens the negative environmental impact.

While current laboratory costs for producing bio-based materials for packaging are high, they are expected to decrease with the scaling up the production and optimization of processes. This will lead to economies of scale and increased manufacturing efficiency. As result, bio-based packaging materials have substantial economic and environmental potential, contributing to sustainable development and reducing environmental impact.

2.3.2.4. Production of NCs

The process for production of NCs is still energy-intensive and requires specialized materials for stabilizing active ingredients (Table 4).

Table 4 LCC for production of NCs

LCC NCs	
Cost items	**Costs [EUR]**
Material Costs	63.16
Energy Costs	0.10
Total Costs	**1 kg [EUR]**
Process NCs	63.26

- Economic Feasibility: High unit costs due to the specialized materials and energy requirements, but the NCs market holds substantial potential.
- Potential for Cost Reduction: Advances in micro- and nanofabrication technologies could reduce production costs.
- Environmental Benefits: The use of biodegradable polymers and reduced chemical waste can improve environmental outcomes.

The implementation of bio-based antimicrobial NCs can significantly enhance both economic and environmental value, particularly if the process is optimized for cost efficiency.

2.3.2.5. PUR foam production

PUR foam is widely used as a material for shoe (in)soles due to its exceptional cushioning properties, light weight, durability, and ability to provide comfort while walking. These characteristics make PUR foam a promising choice for the footwear industry, especially within the scope of this project, which aims to develop durable and environmentally sustainable soles.

Table 5 LCC for a-PHB-based PUR foam

LCC PUR foam	
Cost items	**Costs [EUR]**
Material Costs	28.37
Energy Costs	1.04
Total Costs	**1 kg [EUR]**
Process PUR foam	29.41

- Economic Feasibility: Despite high unit costs due to substantial material and energy expenses, PUR foam production remains economically justified (Table 5). The high demand and widespread application of PUR foam help offset these costs. Its competitive advantages, such as versatility and durability, make this material highly sought-after, even with relatively high production costs.
- Potential for Cost Reduction: There are significant opportunities for cost optimization in PU foam production. Innovations in manufacturing, such as sourcing alternative raw materials (e.g., shifting to bio-based polymers), implementing waste recycling initiatives, and improving energy efficiency, can help considerably reduce costs. Gradual adoption of recycled or lightweight materials can reduce material expenses and improve production efficiency.
- Environmental Benefits: PUR foam production has some environmental impact, as it is non-biodegradable and requires significant energy input. However, switching to more sustainable and eco-friendly materials, such as renewable polymers or recyclable PUR systems, could reduce this impact. Additionally, reducing chemical waste, lowering CO_2 emissions, and transitioning to renewable energy sources during production can greatly improve the product's environmental profile.

Overall, optimizing the PUR foam production process through the adoption of eco-friendly materials and energy-efficient technologies can enhance both the economic and environmental value of this material. Developing and improving such solutions will not only lower costs but also support modern environmental responsibility standards, making PUR foam more appealing to eco-conscious markets.

2.3.2.6. Printing processes with bio-based inks

The LCC results for digital printing Scenarios described in the LCA-section are presented in Table 6.

Table 6 LCC for printing Scenarios 1-3

Scenario1

Cost items	Costs [EUR]
Material Costs	5.56
Energy Costs	2.16
Total Costs	**1 kg [EUR]**
Process S1	7.72

Scenario2

Cost items	Costs [EUR]
Material Costs	2.84
Energy Costs	6.13
Total Costs	**1 kg [EUR]**
Process S2	8.97

Scenario3

Cost items	Costs [EUR]
Material Costs	5.81
Energy Costs	6.13
Total Costs	**1 kg [EUR]**
Process S3	11.94

- Economic Feasibility: In principle, these bio-inks demonstrate potential for cost reduction compared to traditional inks, as they are more sustainable and utilize renewable materials. However, the high energy costs, especially in Scenarios 2 and 3, may reduce the economic viability unless these costs are further lowered with upscaling.
- Potential for Cost Reduction: As demonstrated by the recycling methods analysis, production costs for materials and energy should decrease with industrial upscaling. This suggests that there is potential for further cost reduction in the future through process optimization and bulk purchase of materials. Furthermore, the application of these inks in the inkjet equipment developed in the project (using piezoelectric printheads) would lead to further reduction as they require much less ink and no drying step.
- Environmental Aspects: The use of bio-inks helps to reduce negative environmental impacts by utilizing safer and renewable materials. This also contributes to waste reduction, whereas the incorporation of biopolymers improves the longevity of the product. However, it is important to consider that, although these processes are more environmentally friendly, they still require significant amounts of energy and water.

Bio-inks can help reduce the environmental footprint by decreasing the use of toxic components, while simultaneously promoting sustainable development.

To reduce costs and improve economic feasibility, scaling up production is essential, as it can lower energy and material costs, making the process more cost-effective and more efficient.

2.3.2.7. Chemical Recycling Processes for PHAs

LCC analysis of TD, AH, and CM as key chemical recycling methods for PHAs was conducted (Table 7). While lab-scale results provide valuable insights, costs and effectiveness may change significantly by transfer to industrial level. It is expected that production costs and energy efficiency will improve with scaling, influencing the economic feasibility of each recycling method.

Table 7 LCC of chemical recycling

LCC Go!PHA TD

Cost items	Costs [EUR]
Material Costs	26.61
Energy Costs	2.63
Total Costs	**1 kg [EUR]**
Process TD	29.24

LCC Go!PHA AH

Cost items	Costs [EUR]
Material Costs	29.07
Energy Costs	1.25
Total Costs	**1 kg [EUR]**
Process AH	30.32

LCC Go!PHA CM

Cost items	Costs [EUR]
Material Costs	38.89
Energy Costs	2.54
Total Costs	**1 kg [EUR]**
Process CM	41.43

- Economic Feasibility: All three recycling methods can be profitable from a secondary raw material perspective, but energy and material costs remain high.
- Potential for Cost Reduction: While laboratory costs appear high, industrial scaling often reduces unit costs. Large-scale production and the potential for continuous processing can lower material and energy costs through bulk procurement and improved process efficiency.
- Environmental Aspects: Reducing waste and utilizing secondary materials positively impacts the ecological footprint, although CO_2 emissions and energy consumption must be considered. The environmental benefits of each method align with the goals of the **W2BC** project, as bio-based polymers support a circular economy, reducing reliance on synthetic materials and encouraging reuse in production cycles.

2.3.3. General conclusions on the LCC

Development of advanced technologies and processes has potential to reduce emissions and energy costs, positively impacting their ecological footprint. All investigated methods hold promise for cost reduction and improved efficiency through technology innovation, production upscaling, and the development of alternative energy sources.

The production of bio-based materials for soft packaging, as well as for textiles and footwear, holds significant economic and environmental potential. While current laboratory costs reflect a high initial investment, these costs are expected to decrease by production scale-ups and optimisation of processes. Achieving economies of scale and process efficiency is crucial to realizing the full potential of bio-based materials developed in frame of **W2BC** project.

Following general conclusions for processes, where data could not be provided by partners due to confidentiality reasons, was made based on the literature on LCC:

- Materials and Raw Materials: Studies in the literature emphasize the shift towards using more sustainable materials, like bioplastics (e.g., PHAs) and natural dyes/pigments, which offer environmental advantages, such as biodegradability and reduced reliance on non-renewable resources. These materials often incur higher initial costs compared to conventional plastics and synthetic dyes. However, optimizing production technologies and scaling up production volumes can reduce these costs in the long-term scenarios.
- Energy Consumption: Various studies suggest that processes involved in the production of bioplastics and natural dyes/pigments can require substantial energy input, especially during stages like synthesis, processing, and dyeing. As production scales up and renewable energy sources are incorporated, energy costs can be lowered. Furthermore, innovations in energy-efficient technologies can make these processes more economically viable.

- Environmental Impact: The environmental advantages of using biomaterials are well-documented, with significant reductions in carbon footprints and waste production compared to traditional synthetic materials. However, challenges still exist at production and disposal stages, particularly regarding water waste management and resource consumption. Effective waste and resource management strategies are crucial to minimizing the ecological footprint of such processes.

There are certain processes for which conducting LCC calculations currently makes little sense due to unsatisfactory LCA results and incomplete or unreliable data regarding electricity consumption and its scaling. Within the context of upscaling specific processes, these limitations prevent even a relatively approximate estimation of LCC, unlike in processes where calculations have already been performed.

At this stage of the research, the overall situation remains challenging not only within the scope of the **W2BC** project, but also across the broader field. Research institutions often lack access to the detailed and reliable data required for informed analysis. At the same time, industrial stakeholders typically regard such information as confidential and commercially sensitive.

As result, even the LCC estimates that can be generated are likely to deviate significantly from real-world conditions. They will not include the complete financial input data necessary for a credible LCC assessments.

2.4. Social LCA (SLCA)

2.4.1. Data collection

In the context of modern research on sustainable development and the circular economy, social aspects are playing an increasingly important role as a component in assessing the impacts of production processes. The evaluation of social impacts, particularly through the SLCA (Social Life Cycle Assessment) methodology, is becoming an integral part of implementing sustainable production principles. One of the main strategic frameworks is the Sustainable Development Goals (SDGs) — 17 global goals adopted by the United Nations in 2015 as part of the Agenda 2030. These goals aim to address poverty, inequality, climate change, natural resource protection, and the advancement of a sustainable economy. To effectively implement the SLCA approach, a data collection template has been developed, based on several international standards and regulatory documents, divided into mandatory (regulatory) and voluntary categories (Figure 24):

Mandatory EU Regulatory Frameworks:

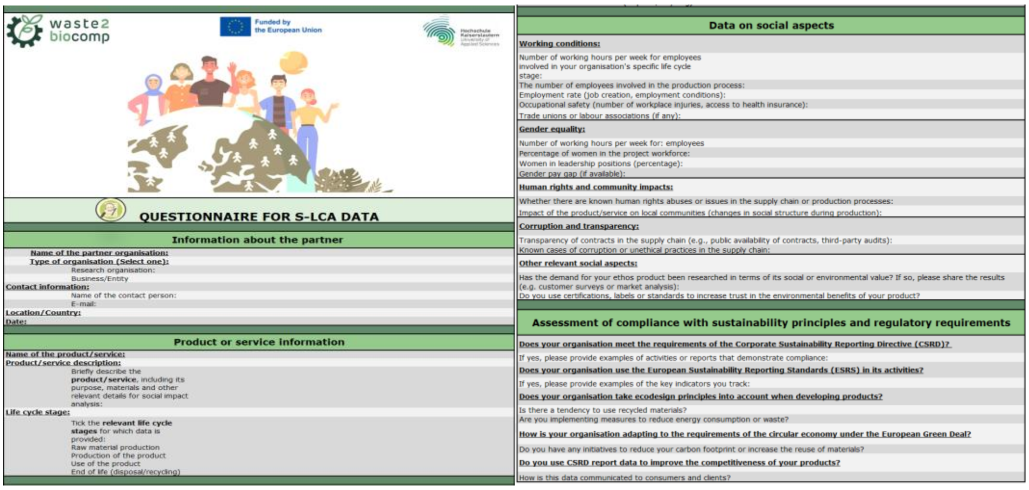
- Corporate Sustainability Reporting Directive (CSRD): An EU directive requiring mandatory non-financial reporting for large companies.
- European Sustainability Reporting Standards (ESRS): A set of detailed indicators aligned with the CSRD.
- Eco-design Directive: Requirements for the environmental performance of products at the design stage.
- European Green Deal: A strategy for achieving climate neutrality by 2050 through the transformation of the EU economy.
- General Data Protection Regulation (GDPR): A regulation ensuring the protection of personal data, including employee-related information.

Voluntary International Standards:

- ISO 26000: Guidelines on social responsibility.
- SA8000: A standard for ensuring decent working conditions (occupational safety, workers' rights, and the prohibition of child and forced labour).

In addition, the template incorporates the principles of the UN Guiding Principles on Business and Human Rights, the Universal Declaration of Human Rights, and considers potential risks related to the geographical location of production and the origin of raw materials.

Thus, the SLCA data collection system is built on a combination of binding regulations and voluntary ethical standards, enabling a comprehensive assessment of corporate social responsibility within the framework of sustainable development.



waste2 biocomp

Funded by the European Union

Hochschule Kaiserslautern University of Applied Sciences

QUESTIONNAIRE FOR S-LCA DATA

Information about the partner

Name of the partner organisation:
Type of organisation (Select one):
Research organisation:
Business/Entity
Contact information:
Name of the contact person:
E-mail:
Location/Country:
Date:

Product or service information

Name of the product/service:
Product/service description:
Briefly describe the **product/service**, including its purpose, materials and other relevant details for social impact analysis:
Life cycle stage:
Tick the **relevant life cycle stages** for which data is provided:
Raw material production
Production of the product
Use of the product
End of life (disposal/recycling)

Data on social aspects

Working conditions:
Number of working hours per week for employees involved in your organisation's specific life cycle stage:
The number of employees involved in the production process:
Employment rate (job creation, employment conditions):
Occupational safety (number of workplace injuries, access to health insurance):
Trade unions or labour associations (if any):

Gender equality:
Number of working hours per week for: employees
Percentage of women in the project workforce:
Women in leadership positions (percentage):
Gender pay gap (if available):

Human rights and community impacts:
Whether there are known human rights abuses or issues in the supply chain or production processes:
Impact of the product/service on local communities (changes in social structure during production):

Corruption and transparency:
Transparency of contracts in the supply chain (e.g., public availability of contracts, third-party audits):
Known cases of corruption or unethical practices in the supply chain:

Other relevant social aspects:
Has the demand for your ethos product been researched in terms of its social or environmental value? If so, please share the results (e.g. customer surveys or market analysis):
Do you use certifications, labels or standards to increase trust in the environmental benefits of your product?

Assessment of compliance with sustainability principles and regulatory requirements

Does your organisation meet the requirements of the Corporate Sustainability Reporting Directive (CSRD)?
If yes, please provide examples of activities or reports that demonstrate compliance:
Does your organisation use the European Sustainability Reporting Standards (ESRS) in its activities?
If yes, please provide examples of the key indicators you track:
Does your organisation take ecodesign principles into account when developing products?
Is there a tendency to use recycled materials?
Are you implementing measures to reduce energy consumption or waste?
How is your organisation adapting to the requirements of the circular economy under the European Green Deal?
Do you have any initiatives to reduce your carbon footprint or increase the reuse of materials?
Do you use CSRD report data to improve the competitiveness of your products?
How is this data communicated to consumers and clients?

Figure 24 Structure and focus of the SLCA data collection template.

To ensure a comprehensive assessment, a template was developed that covers following key social indicators:

Section 1: Company Identification:

- Name, sector, contact person, location.

Section 2: Product / Service:

- Description, purpose, raw materials, technologies, eco-design principles, product life cycle duration.
- Market analysis, social value, linkage to SDGs.
- Presence of LCA (ISO 14040 / 14044), impacts, design adaptation.

Section 3: Social Aspects:

A. Working Conditions (SDG 8):

- Working hours, employment conditions, safety, medical care, trade unions, legal compliance.

B. Gender Equality and Inclusion (SDG 5):

- Proportion of women overall and in management, gender pay gap, maternity policy, non-discrimination.

C. Human and Community Rights:

- Human rights violations, community involvement, contribution to development, educational programs.

D. Digital Rights and Well-being (GDPR, digitalization of work):

- Data protection, ethical monitoring, cybersecurity, mental health, work-life balance.

E. Transparency and Anti-corruption (SDG 16):

- Contract transparency, audits, abuse reports.

F. Additional Indicators (ISO 26000, SA8000, Fair Trade):

- Presence of certifications, consumer feedback, confirmation of social or environmental value of the product.

2.4.2. SLCA results

Here is the list of the 17 Sustainable Development Goals (SDGs), which serve as reference "steps" for interpreting SLCA results. These globally recognized targets help evaluate corporate social responsibility in a structured and internationally aligned way:

(SDG 1) No Poverty

• Elimination of poverty among employees and in production-related communities.

(SDG 2) Zero Hunger

• Contribution to food security and nutrition, especially in agri-food sectors.

(SDG 3) Good Health and Well-being

• Workplace safety, occupational health, and mental well-being of employees.

(SDG 4) Quality Education

• Training, skill development, and access to learning opportunities for workers.

(SDG 5) Gender Equality

• Women's participation, inclusive HR policies, and equal pay practices.

(SDG 6) Clean Water and Sanitation

• Access to water and sanitation for workers and sustainable water use practices.

(SDG 7) Affordable and Clean Energy

• Use of renewable energy sources and improving energy efficiency.

(SDG 8) Decent Work and Economic Growth

• Fair wages, job security, working hours, and safe labor conditions.

(SDG 9) Industry, Innovation, and Infrastructure

• Technological innovation, eco-design, and industrial modernization.

(SDG 10) Reduced Inequalities

• Promoting equal opportunities and anti-discrimination measures.

(SDG 11) Sustainable Cities and Communities

• Social impact on local communities and urban infrastructure.

(SDG 12) Responsible Consumption and Production

• Resource efficiency, biodegradable materials, and circular design.

(SDG 13) Climate Action

• CO_2 reduction strategies and climate adaptation efforts.

(SDG 14) Life Below Water

• Protection of marine ecosystems and avoidance of microplastic pollution.

(SDG 15) Life on Land

• Biodiversity conservation and sustainable land use.

(SDG 16) Peace, Justice and Strong Institutions

• Transparency, anti-corruption, and respect for human rights.

(SDG 17) Partnerships for the Goals

• Participation in global initiatives and reporting via frameworks such as CSRD, GRI, and ISO.

The indicators from each Section related to **W2BC** project are presented below based on the data provided.

2.4.2.1. Section 1: Company Identification

Company	Type of Organisation	Sector / Activity	Country
PILI	Manufacturing	Chemistry, Biotechnology	France
Nora systems	Manufacturing	EVA Materials, Flooring Solutions	Germany
PROPAGROUP	Manufacturing	Packaging	Italy
Riopele – Têxteis	Business / Company	Textile Industry (Sportswear)	Portugal

Purpose of the Section

Provides core identification details about each organization, including its sector, type of activity, and key contact person. This section helps assess the role of each partner in the development of bio-based and sustainable materials within the project.

Results

All listed organizations are actively involved in the project, contributing to eco-oriented production and innovative materials development. Geographically, the group covers key EU countries: France, Germany, Italy, and Portugal. To ensure the integrity and applicability of results, this section includes only manufacturing enterprises directly involved in material production.

2.4.2.2. Section 2: Product / Service Information

Company	Product	Ecodesign	Bio-/Compostability	LCA / CO_2	Market Analysis / Trends	Social Value / SDG
PILI	Bio Indigo (dye)	Yes	Yes	CO_2↓ >50%	Yes (denim market)	SDG 3, 6, 9, 12, 13
Nora	Biofoam (for insoles)	Yes	Yes (compostable)	Not available	Not available	General social value
꞉OPAGROUP	Flexible PHA-based packaging film	Yes	Yes (fully compostable)	Not available	Yes	SDG 12 (waste reduction)
Riopele	Technical textile for sportswear	Yes	Partial (PLA + recycled PES)	Not available	Not available	SDG 12 (eco-structured textile)

Purpose of the Section

To assess the environmental performance, level of innovation, eco-design integration, market orientation, and social value of each product in the context of sustainable development.

Results & Interpretation

All manufacturing partners demonstrate commitment to sustainable innovation through the development of bio-based or compostable materials. Eco-design principles are systematically applied across the board, and there is a clear orientation toward reducing environmental impact.

- Eco-design is embedded in all products from the development stage onward.
- Bio-based content is a defining feature of each solution:
  - PILI and PROPAGROUP deliver fully compostable materials.
  - RIOPELE combines recycled PET and PLA to avoid microplastics and enhance biodegradability.
  - NORA presents a compostable bio-foam, though without supporting environmental metrics.
- Lifecycle metrics are limited. Only PILI has performed LCA, showing more than 50% CO_2 reduction compared to conventional indigo production.
- Market maturity varies:
  - PILI provides clear market validation, pilot applications, and trend alignment (luxury denim).

Interpretation:

- PILI leads in sustainable integration, combining environmental data, eco-certification, and market uptake. It clearly aligns with multiple SDGs and provides a replicable model for responsible product innovation.

- PROPAGROUP presents a well-aligned compostable packaging solution with potential for immediate application, particularly in sectors addressing plastic waste.
- NORA has a strong ecological narrative but lacks evidence through LCA or engagement data to position it competitively in the green innovation space.
- RIOPELE contributes to material-level innovation, especially in recycling and biodegradability, but further validation (CO_2, reuse potential, user acceptance) would strengthen its positioning.

2.4.2.3. Section 3A: Working Conditions

Company	Working Hours	Employees	Employment Conditions	Occupational Safety / Insurance
PILI	38 (flexible)	46	90% permanent, supports apprentices	100% insured, only 3% absenteeism
Nora	37	546	87% permanent, others on fixed/trainee contracts	17 injuries (2024), health program in place
PROPAGROUP	40	30	Governed by Italian "Gomma Plastica" contract	ISO 45001 certified, SMETA compliance
Riopele	40	826	Not specified	50 injuries (2024), workplace accident insurance

Purpose of the Section

To evaluate the company's commitment to providing fair, safe, and stable employment conditions, in alignment with international labour standards (ILO) and Sustainable Development Goal 8: Decent Work and Economic Growth.

Results & Interpretation

All four companies demonstrate basic compliance with the principles of decent work, as defined by ILO is a specialized agency of the UN focused on labor issues - Convention No. 1 and SDG 8 (Decent Work and Economic Growth). The assessment covers working hours, workforce size, employment types, occupational safety, and the presence of trade unions.

- Working hours do not exceed 40 per week, aligning with EU and ILO norms (Figure 25).
- Employment stability is generally high, with most companies reporting over 85% permanent contracts.
- Occupational safety and insurance are in place across all companies, though reported injury rates vary significantly (from 17 to 50 cases).
- Trade union representation is reported only by RIOPELE, indicating structured social dialogue mechanisms.
- PILI ensures the highest level of social protection under a flexible schedule, with low absenteeism indicating a healthy balance between productivity and well-being.
- NORA has the largest share of permanent employees and an active health program. Its workplace injury rate is moderate.
- PROPAGROUP operates under a national collective agreement, with confirmed compliance through ISO 45001 and SMETA standards.
- RIOPELE employs the largest workforce but also reports the highest number of workplace accidents. However, the presence of multiple trade unions supports structured worker representation and potential safety improvements.

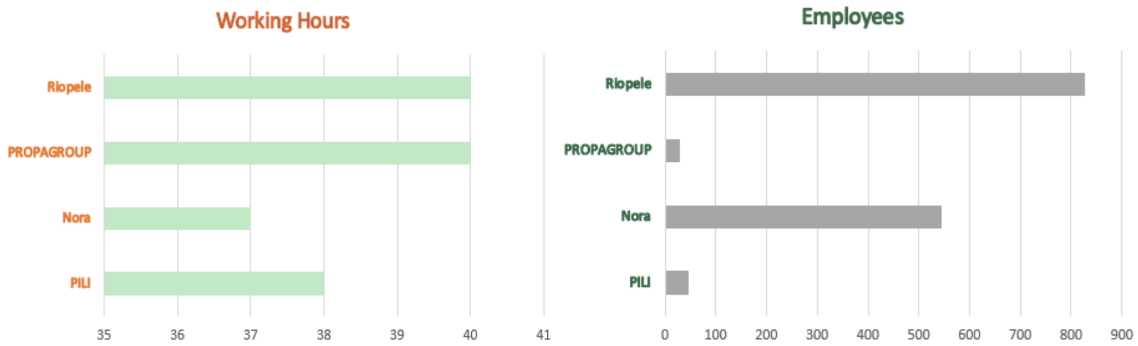


Figure 25 Working hours and number of employees at four manufacturing companies.

Additional Information (RIOPELE)

Trade Unions / Workers' Associations:

- SINDEQ – Sindicato das Indústrias e Afins
- Sindicato Confeção Vestuário de Braga
- Têxtil Minho e Trás os Montes

RIOPELE has the highest number of employees among all partners, highlighting its social significance. The presence of several trade unions indicates a well-organized labour structure, although the number of injuries (50 cases) calls for further attention to occupational safety.

2.4.2.4. Section 3B: Gender Equality & Inclusion

Company	Women in Workforce (%)	Women in Leadership (%)	Gender Pay Gap	Inclusion / Anti-discrimination Measures
PILI	54%	64%	Tracked and corrected	Inclusive policy, training, adaptive workplace
Nora	—	17%	Not provided	General policy exists, no actions in place
PROPAGROUP	25%	5%	Not provided	SMETA, whistleblowing system, legal compliance
Riopele	38%	44%	Not provided	Not reported

Purpose of the Section

To evaluate gender participation, equality in pay, leadership representation, and the presence of inclusive, non-discriminatory policies within the organization. This section aligns with SDG 5: Gender Equality and related ILO conventions.

Results & Interpretation

All companies provided at least partial data on gender composition.

- Only PILI reported actively monitored pay equity and inclusive policies.
- RIOPELE demonstrates relatively balanced female participation (38%) and leadership (44%), but without reporting on policy frameworks.
- PROPAGROUP shows a significant gender gap in leadership, with only 5% women in decision-making roles.
- NORA reported 17% of women in leadership but did not provide full workforce or wage gap data.

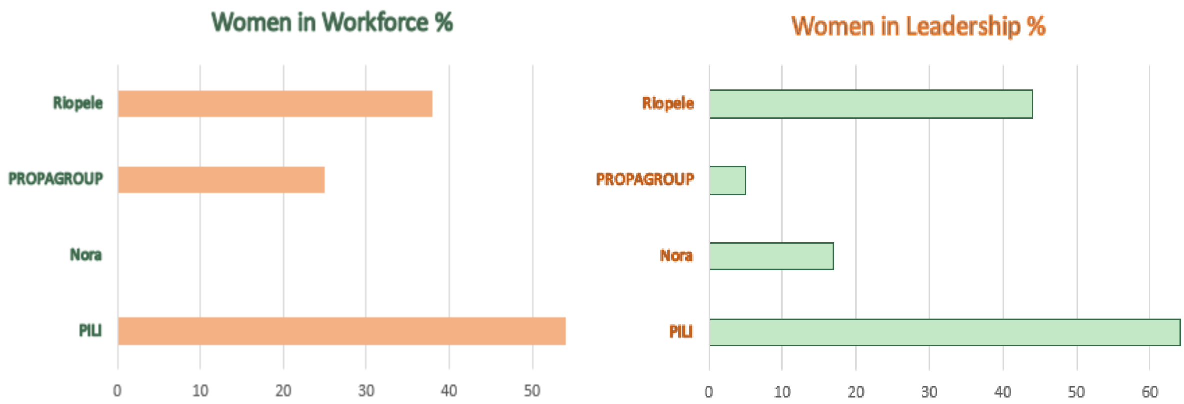


Figure 26 Percentage of women in both Workforce and Leadership positions.

- PILI leads in both representation and system-level commitment to gender equity, aligning with best practices.
- PROPAGROUP and NORA need to improve transparency and apply actionable measures, particularly in decision-making access.
- RIOPELE shows promising numbers on inclusion but lacks policy disclosure to confirm sustainable impact.

2.4.2.5. Section 3C: Human Rights & Community Impact

Company	Human Rights Violations	Community Engagement	Employee Development
PILI	None	Through local associations	100% of employees received training
Nora	None	Major employer in Weinheim	Individual training plans for managers
PROPAGROUP	None	Not specified	Training program implemented
Riopele	None	No recorded community impact	Training hours per employee are monitored

Purpose of the Section

This section assesses whether the company upholds human rights within its own operations and supply chains and evaluates the extent of its engagement with local communities and contribution to social stability.

Results & Interpretation

All companies comply with fundamental human rights principles, with no reported violations in their supply chains.

- PILI stands out for its strong transparency and commitment to employee development.
- RIOPELE operates on the largest scale but shows limited active engagement with local communities.
- PROPAGROUP and NORA focus primarily on internal training programs with less emphasis on external social impact.

2.4.2.6. Section 3D: Digital Rights & Well-being

Company	Data Protection	Employee Monitoring	Mental Health Support	Work-Life Balance
PILI	GDPR compliant	None	Events, internal consultations	Teleworking, internal surveys
Nora	Yes	Not specified	Health program, staff surveys	Not specified
PROPAGROUP	Yes	In place	Support program implemented	In place
Riopele	Yes	Not specified	Not specified	Not specified

Purpose of the Section

This section assesses how companies protect employees' personal data, comply with digital ethics, and support mental health and work-life balance. It aligns with GDPR and SDG 3: Good Health and Well-being.

Results & Interpretation

- PILI demonstrates the most comprehensive approach to digital rights and employee well-being.
- PROPAGROUP has formal mechanisms in place, though without detailed information on supportive measures.
- NORA implements isolated initiatives but does not fully address the topic of work-life balance.
- RIOPELE provides a basic level of data protection but does not report on digital ethics or well-being programs.

2.4.2.7. Section 3E: Transparency & Anti-Corruption

Company	Supply Chain Transparency	Corruption Incidents
PILI	Internal control mechanisms	None reported
Nora	ISO 9001, ISO 14001, ISO 50001	None reported
PROPAGROUP	SMETA, ISO 45001, whistleblowing system	None reported
Riopele	Public sustainability report (CSRD / GRI)	None reported

Purpose of the Section

This section assesses the existence of transparency mechanisms in the supply chain, the use of third-party audits, any reported corruption cases, and the overall level of business integrity.

Results & Interpretation

All companies maintain a basic level of transparency.

- PROPAGROUP demonstrates the most advanced control system through certifications (SMETA, ISO 45001) and anonymous reporting mechanisms.
- RIOPELE ensures transparency through public sustainability reporting based on CSRD and GRI standards.
- NORA Systems applies certified management systems (ISO 9001, 14001, 50001), which provide structured control but lacks disclosure on audit results or whistleblowing practices.
- PILI relies on internal control mechanisms but lacks external verification.

2.4.2.8. Section 3F: Other Relevant Social Indicators

Company	Certifications / Standards	Social / Environmental Value
PILI	ZDHC MRSL Level 1	Yes
Nora	Blue Angel, Cradle2Cradle, EPD	Yes
PROPAGROUP	SMETA, ISO 45001	Yes
Riopele	GRI-based sustainability report	Yes, communicated through website, surveys, and visits

Purpose of the Section

This section assesses the use of voluntary certifications (e.g., ISO, ZDHC, Cradle2Cradle), the demonstrated social and environmental value of products, customer surveys, and feedback mechanisms.

Results & Interpretation

All companies hold environmental certifications or publish sustainability reports, reinforcing their reputation as responsible producers.

- RIOPELE stands out for its active public communication through CSRD reporting, website content, and newsletters.
- PILI and NORA demonstrate verified environmental value through internationally recognized eco-labels.
- PROPAGROUP complies with SMETA requirements and implements sustainable production policies.

2.4.3. General conclusions on the SLCA

The SLCA conducted across four European manufacturing companies (partners PILI, NORA, PROPAGROUP, and RIOPELE) demonstrates that social sustainability is gradually becoming an integral part of innovation and materials development.

Key strengths across the companies

- No reported human rights violations or unethical practices in supply chains.
- Social and environmental certifications (e.g., ZDHC, ISO, SMETA, Blue Angel) confirm alignment with SDGs and market expectations.
- Responsible working conditions: All companies ensure formal employment, occupational safety, and basic health coverage, aligning with ILO conventions.
- Commitment to sustainability is evident through eco-design implementation, use of bio-based or recyclable materials, and emission reduction goals.

Differentiating factors

- PILI leads in gender equality, digital well-being, and stakeholder communication, offering a highly integrated sustainability approach.
- RIOPELE demonstrates strong institutional reporting (GRI/CSRD), active decarbonisation efforts, and large-scale employee training-though with less focus on community engagement.
- PROPAGROUP stands out for its formal transparency infrastructure, though social aspects are less developed beyond compliance.
- NORA implements several sustainability measures but lacks full transparency in digital rights, gender policy, and social outreach.

Observed gaps

- Incomplete data across companies regarding mental health, work-life balance, and impact on local communities.
- Limited engagement with social innovation beyond internal training.
- Varying levels of external verification and use of voluntary social standards.

Final assessment

The companies assessed represent different stages of maturity in implementing SLCA-relevant practices. While all meet minimum standards in labour rights and product responsibility, only some demonstrate a proactive, systemic approach to social sustainability. Strengthening transparency, stakeholder engagement, and community-oriented innovation will be key to aligning further with Agenda 2030 and EU regulatory frameworks.

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