BIO4HUMAN

D5.2

Hotspot analysis of the current and innovative solutions

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List of Abbreviations

Abbreviation	Meaning
AD	Anaerobic Digestion
B4H	Bio4HUMAN
BSF	Black Soldier Fly
C	Carbon
CF	Characterisation Factor
CH_4	Methane
CH_4,b	Biogenic methane
CO_2	Carbon dioxide
CO_2,b	Biogenic carbon dioxide
DM	Dry Mass
DRC	Democratic Republic of Congo
DX.X	Deliverable X.X
E	10^x (2,5E-02 = $2,5*10^{-2}$ = 0,025 or 2,05E+02 = $2,05*10^2$ = 205)
EF	Environmental Footprint
EF3.1	Environmental Footprint 3.1 (LCIA methodology)
E-LCA	Environmental Life Cycle Assessment
EoL	End-of-Life
Eq	Equivalent
ERU	Emergency Response Unit
EU	European Union
EVI	Economic Vulnerability Index
FSI	Food Security Index
FU	Functional Unit
GLO	Global
HA	Humanitarian Aid
HDPE	High-Density PolyEthylene
HO	Humanitarian Organisation
IW+	Impact World + (LCIA Methodology)
K	Potassium
$kgCO_2$ eq	kilogram CO_2 equivalent
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCIA	Life Cycle Impact Assessment
LCSA	Life Cycle Sustainability Assessment
LDPE	Low-Density PolyEthylene
MDI	Material Durability Indicator
Mt	Million(s) of tonnes
N	Nitrogen
NFI	Non-Food Items
P	Phosphorous
PDF·m^2·yr	Potentially Disappeared Fraction of species over an area during a year
PE	PolyEthylene
PEF	Product Environmental Footprint
PP	PolyPropylene

PUR	Poly URethane
PVC	Poly Vinyl Chloride
RER	Rest-of-Europe
RoW	Rest-of-World
RUTF	Ready-to-Use Therapeutic Food
S-LCA	Social Life Cycle Assessment
SS	South Sudan
UC	Universidad de Cantabria (partner of B4H)
WASH	WAter, Sanitation and Hygiene
WDI	Water Depletion Index
WGI	Worldwide Governance Indicator

Publishable Summary

The main objective of Bio4HUMAN Task 5.2 was to carry out a hotspot analysis of the reference items and innovative solutions, using the inventories collected during Task 5.1 *Data collection from partners: state-of-the-art collection from partners: state-of-the art and innovative solutions*. The inventories were analysed, and the modifications are reported in this deliverable together with the methodology applied and the identification of environmental hotspots. This deliverable is structured into five sections: a review of previous studies in *II. State of the Art*, a description of the hotspot analysis methodology in *III. Methodology*, a presentation of the inventories in *IV. Inventory*, the analysis results in *V. Life cycle impact assessment*, and an assessment of the geographical availability of the solutions in *VI. Geographic availability assessment*.

In the first section, a **state-of-the-art** of LCA study in the context of humanitarian aid (HA) is conducted to identify relevant environmental impact categories, the methodologies applied, common hotspots, and the main challenges faced. Six studies, both qualitative and quantitative, were analysed, some of which were conducted in an African context. This ensures a fair comparison with the case studies of the Bio4HUMAN project conducted the Democratic Republic of Congo (DRC) and South Sudan (SS).

The second part is focused on describing the Life Cycle Impact Assessment (LCIA) **methodology** used to identify environmental hotspots. Several indicators from the Environmental Footprint 3.1 (EF3.1) method were selected to reflect the environmental challenges faced by the two countries. In addition, European projects focusing on biobased scope were reviewed to identify specific indicators that enable a fair comparison between fossil-based and biobased items in the subsequent Task 5.3.

The third section provides the **inventories** updated from D5.1 and **results** of the hotspot analysis for the reference and solution items, expressed per kilogram of product. For each item, the main sources of environmental impact were identified. A functional unit comparison is not included at this stage, as it will be developed in Task 5.3.

The final section includes a **geographical availability** assessment by considering the influence of local energy mixes in the DRC and SS, to highlight the advantages and limitations of producing solutions locally. This section also integrates the waste collection at End-of-Life (EoL), and an example of a criticality assessment, comparing a biobased solution with its fossil-based reference. This helps to capture additional challenges related to biobased materials, such as potential competition with food resources.

Overall, the hotspot analysis conducted in Task 5.2 represents a **preliminary** step for the comparative assessment between solutions and reference items, as well as for the formulation of policy recommendations, which will be carried out in *Task 5.3 Identification of the best available innovative solutions based on environmental LCA*.

I. Introduction

In humanitarian actions, the generated solid waste can accumulate quickly and in large amounts, which has clear potential impacts on public health, livelihood and the environment.

According to the June 2022 questionnaire developed by French independent think tank - *Groupe URD and disseminated among humanitarian organizations in Europe*, the highest concern for the sector constitutes packaging, followed by electronic waste (e-waste), organic waste, sanitation, construction, and medical waste. September 2022 GLC-led WREC project Baseline survey called *Sustainable Supply Chains*[1] states that the most common packaged products used or distributed by humanitarian organizations are plastic packaging (44%), followed by paper and cardboard (43%).

In this context, bio-based solutions and compostable materials represent a viable approach to addressing the issue of solid waste, as they are designed to be treated at its EoL through technologies such as composting or anaerobic digestion, among others. The assistance to analyse bio-based solutions that can fit into humanitarian contexts is done through the Bio4HUMAN project.

The general objective of the project is to "*Identify bio-based solutions for waste management and reduction applicable to humanitarian sector*". In this regard, Bio4HUMAN is assessing the scope to which bio-based innovative technological solutions and bio-based products identified in WP4, *"D4.2 List of bio-based solutions"*, have the potential to be applied under humanitarian contexts, with the simultaneous reduction of negative effect on the environment. Hence, Life Cycle Assessment (LCA) methodology will be applied to examine the potential of the proposed solutions with regards to reducing the environmental impact.

In this sense, WP5's objective is "to *carry out the Environmental Life Cycle Assessment (E-LCA) of the innovative bio-based solutions identified in WP4*". This deliverable is framed within the second task of this WP5 (T5.2), *Hotspot analysis of the current and innovative solutions.*

The objectives of this task, and thus, also of this deliverable, are:

- To determine the hotspots of the current and innovative bio-based waste management solutions.
- To study the geographical availability whenever possible.
- To provide a first analysis, available for Task 5.3, to support the identification of the best available innovative solutions based on environmental LCA.

II. State of the Art

In recent years, humanitarian organisations have begun to recognise the significant environmental impacts associated with their operations.

Indeed, the WREC/KLU (2024)[2] report shows that in 2023, 23% of surveyed humanitarian actors measured emissions across Scopes 1–3, while this is up to 9%

[1] https://logcluster.org/document/wrec-baseline-survey-results?language=es
[2] WREC/KLU (2024) Measuring the Greenhouse Gas Emissions and Waste of Humanitarian Supply Chains

in 2022. These scopes, as defined by the Greenhouse Gas Protocol[3], cover direct emissions (Scope 1), emissions from purchased energy (Scope 2), and all other indirect emissions, such as transport, procurement, and waste (Scope 3). Although the sector's primary mandate is to save lives and alleviate suffering, growing awareness of climate change, biodiversity loss, and ecosystem degradation has led to increased scrutiny of the environmental footprint of aid delivery. Six studies were found investigating the environmental challenges linked to humanitarian supply chains, emergency logistics, and product lifecycles.

The WREC/KLU (2024) report combines data from a global survey spanning 77 countries, in-depth field case studies in **Chad, Mozambique, and Pakistan**, and life cycle–based environmental assessments. This study offers a comprehensive overview of current practices, challenges, and emerging trends in measuring and managing the environmental impacts of humanitarian logistics and supply chains. Brangeon and Crowley (2020)[4] conduct a global **qualitative** scoping review of how environmental considerations are integrated into humanitarian policy, funding mechanisms, and operational planning across different sectors. Berggren (2020)[5] focuses on a single-country case study in **Uganda**, applying LCA to the deployment of an Emergency Response Unit (ERU) for water treatment by the Swedish Red Cross. Handler et al. (2024)[6] use LCA to compare different supply and production models for water buckets in humanitarian aid, situating their analysis in three countries: **Nepal, SS, and Peru**. Van Kempen et al. (2016)[7] take a comparative approach, conducting a Life Cycle Sustainability Assessment (LCSA) to evaluate the environmental, social, and economic implications of sourcing humanitarian kitchen sets either locally in **Kenya** or internationally from **India**. Anjomshoae et al. (2023)[8] perform a systematic global **qualitative** literature review of humanitarian supply chain research, assessing how sustainability is addressed across a wide range of contexts and methodological approaches. These studies will be used to analyse the environmental concerns identified, the methods and indicators used, and the results and challenges encountered.

Figure 1 shows the geographical scope of the aforementioned quantitative studies:

[3] GHG Protocol
[4] Brangeon & Crowley (2020) Report on Environmental Footprint of humanitarian assistance for DG ECHO, 2020 - Groupe URD
[5] Berggren (2020) Measuring environmental impact in humanitarian operations
[6] Handler et al. (2024) Environmental life cycle analysis of manufacturing options for humanitarian supplies: drinking water containers | Clean Technologies and Environmental Policy
[7] Van Kempen et al. (2016) Using life cycle sustainability assessment to trade off sourcing strategies for humanitarian relief items | The International Journal of Life Cycle Assessment
[8] Anjomshoae et al. (2023) : Full article: Sustainable humanitarian supply chains: a systematic literature review and research propositions

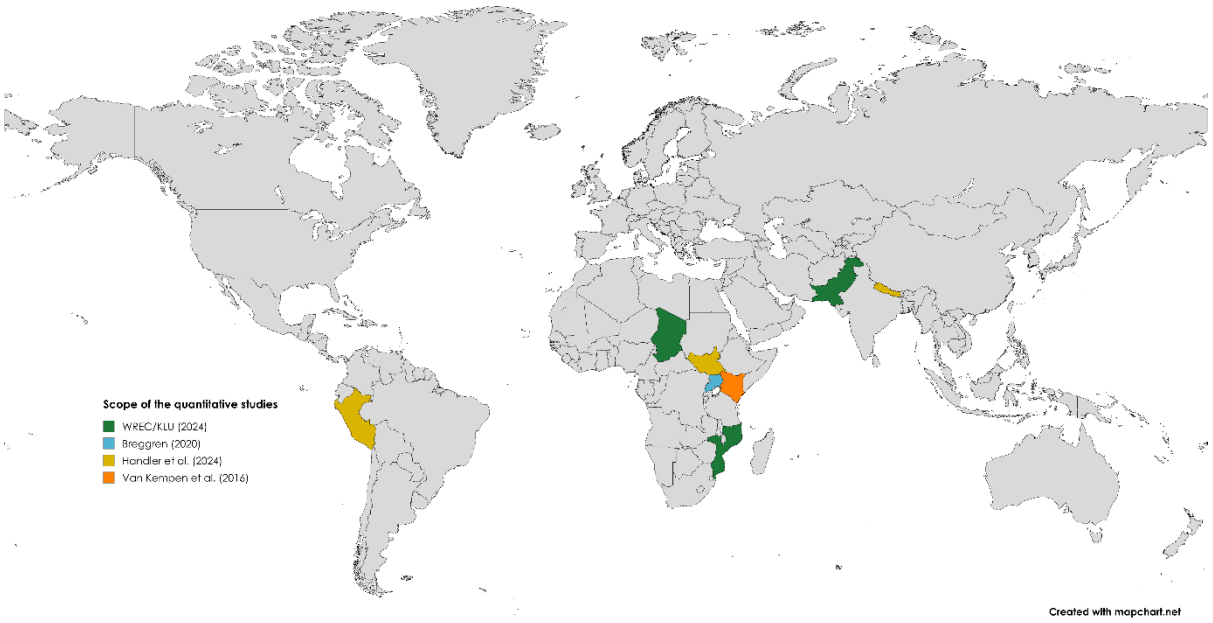


Figure 1 Geographical scope of the quantitative studies (done with MapChart[9])

A. Key environmental challenges addressed by existing studies

Although humanitarian organizations increasingly acknowledge the importance of sustainability, **environmental concerns remain poorly integrated** into humanitarian action. As Brangeon & Crowley (2020) note, issues such as deforestation, CO_2 emissions, and water overuse are rarely addressed systematically and are often deprioritized in funding and program design. Similarly, Anjomshoae et al. (2023) emphasize that sustainability in humanitarian supply chains is still fragmented, with **environmental, social, and economic impacts rarely assessed together**. This lack of integration is reflected across multiple studies, which identify recurring concerns such as greenhouse gas emissions from logistics, high-impact procurement, and poor waste management. Long-distance transport, diesel-powered field operations, and centralized manufacturing are major sources of emissions (Berggren 2020; Handler et al. 2024; WREC/KLU 2024). The widespread use of short-life plastic items, combined with limited recycling and reverse logistics, further contributes to environmental harm (WREC/KLU 2024). Additional concerns include fossil energy dependence, low uptake of recycled materials, and a lack of environmental data and tools in operational planning (Van Kempen et al. 2016). While awareness is growing, comprehensive sustainability remains far from embedded in humanitarian operations.

B. Method used in existing LCA studies

The studies use a mix of qualitative, quantitative, and hybrid methods to assess environmental impacts.

For the qualitative studies, Brangeon and Crowley (2020) do not conduct LCAs themselves but map current sectoral practices and propose environmental

[9] https://www.mapchart.net/

screening tools, such as NEAT+,[10] for integration into program design and grant applications (e.g., DG ECHO's Single Form). NEAT+ (Nexus Environmental Assessment Tool Plus) is a free screening tool developed by UNEP/OCHA to help humanitarian actors identify and assess environmental risks—across WASH (Water, Sanitation and Hygiene), shelter, food security, and livelihoods—during project planning and proposals. Anjomshoae et al. (2023) also conducted a **literature review** using the TCCM framework (Theory, Context, Characteristics, Method). Their global review of over 150 studies concludes that sustainability in humanitarian supply chains is under-theorized and poorly integrated, particularly with regards to social and environmental dimensions.

For the quantitative studies, Berggren (2020) conducted a **cradle-to-grave** LCA of the Swedish Red Cross ERU M40 water treatment unit deployed in Uganda for 6 months during the South Sudanese refugee crisis using ISO 14040/44 standards. The study evaluated environmental impacts across the full life cycle—from raw material extraction to disposal—based on providing water for 40,000 people per day. It focused on categories such as GHG emissions, acidification, eutrophication, and freshwater use, aiming to identify environmental hotspots and guide more sustainable humanitarian water responses. Data is drawn from actual deployment in Uganda, making it one of the few field-grounded humanitarian LCAs.

Handler et al. (2024) conducted a **cradle-to-gate** comparative LCA of six supply chain models for 14L water buckets used in humanitarian aid. The analysis covered Nepal, SS, and Peru, comparing centralized production (e.g. China, Pakistan) with local 3D printing and extrusion using recycled plastic. The functional unit was one delivered bucket, and the main impact category assessed was Global Warming Potential.

WREC/KLU (2024) combine **LCA**, system dynamics modelling, and large-scale surveys. This methodological mix gives it a sector-wide perspective. The case studies examine **cradle-to-grave** environmental impacts across key humanitarian supply chains in Mozambique, Pakistan, and Chad. In Mozambique, the study focused on the procurement, transport, and packaging waste of tarpaulins, assessing EoL handling. In Pakistan, it analysed local sourcing of tarpaulins, including emissions from production and distribution as well as the feasibility of reverse logistics. In Chad, the case study followed the supply chain of Super Cereal Plus, evaluating emissions, transport impacts, and waste generated in refugee camps. All three studies assessed procurement-phase emissions, packaging waste, and opportunities for circular solutions such as reuse and recovery.

Van Kempen et al. (2016) combined different methodologies with LCSA, which integrates **cradle-to-gate** environmental LCA (ReCiPe method), social LCA (UNEP/SETAC guidelines), and life cycle costing (LCC) to compare stainless steel kitchen sets produced locally in Kenya versus internationally from India. This study focuses on production and transport.

[10] Relief Web - The Nexus Environmental Assessment Tool (NEAT+) [EN/ES/FR] (2021)

The table below summarises the methodologies used in the different studies:

Table 1 Indicators assessed in the literature on humanitarian action

Study	Country studied	Type	Main indicators assessed
Brangeon & Crowley (2020)	Global	Qualitative	Environmental mainstreaming, tool usage
Anjomshoae et al. (2023)	Global	Qualitative	Integration of sustainability pillars
Berggren (2020)	Uganda	Quantitative: Cradle-to-grave LCA	GWP, acidification, eutrophication, ozone depletion, water use
Handler et al. (2024)	Nepal, SS, Peru	Quantitative: Cradle-to-gate LCA	Focus on GWP
WREC/KLU (2024)	Several, focus on Chad, Mozambique, and Pakistan	Quantitative: Cradle-to-grave LCA	GHG emissions (Scope 1–3), waste volumes, recyclability, reverse logistics
Van Kempen et al. (2016)	Kenya/India	Quantitative: Cradle-to-gate LCSA	LCA (Recipe), S-LCA (UNEP/SETAC), LCC (costs)

To complement the comparison with an EU project, the Bio4HUMAN's sister project WORM[11] based its study on EF3.1 impact categories (see Annex VIII.C.1). The medical products are not compared to each other, results of each product are shown for the damage categories accounting for the highest environmental impact. Relationship with the planetary boundaries is also explored in this study based on planetary boundaries per capita. In the end, 6 of the EF3.1 impact categories are presented in the WORM *D1.2. LCA for bio-based solutions*[12]:

- Climate Change,
- Freshwater Ecotoxicity,
- Particulate matter,
- Freshwater Eutrophication,
- Fossil Resource Use,
- Mineral Resource Use.

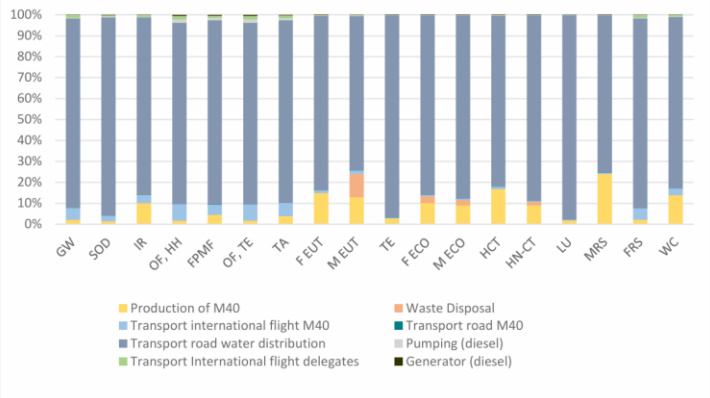
For WORM's *D1.3. LCA of waste treatments*[13], the same categories are considered except for Mineral Resource Use. The D1.3 focuses on average hazardous waste treatments, namely incineration, autoclaving and sanitary landfill, chemical disinfection and sanitary landfill, and microwaving and sanitary landfill. Bio4HUMAN's D5.2, however, attempts to consider biowaste and biodegradable plastics for waste treatment evaluation. Biowaste corresponds to organic waste including agricultural and food waste. To ensure that environmental impacts are not simply shifted from one category to another, all 16 impact categories will be considered, and the EF3.1 hotspot analysis methodology will be applied.

[11] Waste in humanitarian Operations: Reduction and Minimisation - Homepage
[12] D1.2. LCA for bio-based solutions
[13] D1.3. LCA of waste treatments

C. Main hotspots of existing studies

Main sources of impacts in the quantitative studies will be identified to highlight best practices for reducing environmental burdens. Qualitative studies are not considered here, as they do not provide the level of detail or numerical evidence needed to identify environmental hotspots with sufficient precision.

Regarding the results, **Berggren (2020)** finds that road transportation of water from the treatment plant to distribution site is the primary environmental hotspot in the installation of an ERU M40 water treatment unit, followed by production of steel and plastic parts of materials (Figure 2). Impacts from use phase of pumping and electricity generation, as well as the other transportation modes, account for a low share of the impacts. Scenario modelling shows that transport (especially water transport) continues to dominate even with more efficient equipment use. Disposal phase is often unplanned but contributes to long-term burden.



Impact category	Unit	Abbreviation
Global warming	kg CO2 eq	GW
Stratospheric ozone depletion	kg CFC11 eq	SOD
Ionizing radiation	kBq Co-60 eq	IR
Ozone formation, Human health	kg NOx eq	OF, HH
Fine particulate matter formation	kg PM2.5 eq	FPMF
Ozone formation, Terrestrial ecosystems	kg NOx eq	OF, TE
Terrestrial acidification	kg SO2 eq	TA
Freshwater eutrophication	kg P eq	F EUT
Marine eutrophication	kg N eq.	M EUT
Terrestrial ecotoxicity	kg 1,4-DCB	TE
Freshwater ecotoxicity	kg 1,4-DCB	F ECO
Marine ecotoxicity	kg 1,4-DCB	M ECO
Human carcinogenic toxicity	kg 1,4-DCB	HCT
Human non-carcinogenic toxicity	kg 1,4-DCB	HN-CT
Land use	m²a crop eq	LU
Mineral resource scarcity	kg Cu eq	MRS
Fossil resource scarcity	kg oil eq	FRS
Water consumption	m³	WC

Figure 2 Characterized results of life cycle of M40 (Figure 9 from Berggren (2020))

Handler et al. (2023) is the most interesting one for the Bio4HUMAN study, as it compares different scenarios of production of water buckets in different locations, including SS, one of the studied countries of the project. In this study, five scenarios are analysed:

- Model 1: Production with injection moulding in Pakistan from virgin PE, storage in England before shipping
- Model 2: Production with injection moulding in China, from virgin PE and Shipping from China
- Model 3: Production with injection moulding in the destination country, from virgin PE
- Model 4: Production with another less energy intensive production process in the destination country, from virgin PE
- Model 5: Production with yet another lesser energy intensive production process PE in the destination country, from waste

The GWP results for SS are presented in Figure 3. They highlight that SS's almost exclusively oil-based electricity mix is a disadvantage for producing items with energy-intensive manufacturing processes (Models 4 and 5 in both diagrams),

compared to countries like Nepal, which rely primarily on renewable electricity. Overall, carrying out the entire process in countries with fossil fuel–based electricity mixes leads to higher impacts than shipping from external countries (Models 4 and 1). Although using recycled materials can reduce environmental impacts, the benefit is offset by the high carbon intensity of the electricity required. In Model 1, which represents the current scenario, the most impactful stages are raw material production, followed by manufacturing and then shipping. In countries with clean electricity mixes, local production, the use of biowaste, and low-energy technologies help avoid significant environmental impacts.

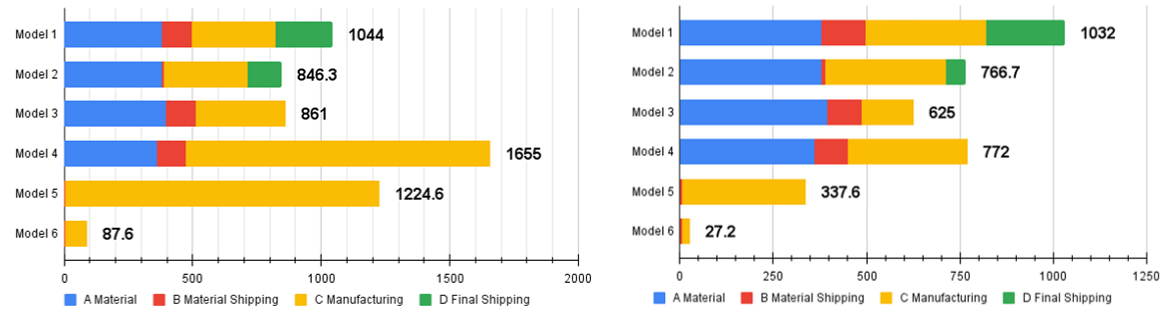


Figure 3 LCA Results South Sudan (right) and Nepal (left) as destination countries (Handler et al. (2024))

The **WREC/KLU (2024)** report adds robust empirical data. Waste tracking has improved to 39% of respondents, but reverse logistics - mechanisms for recovering, reusing, or recycling products after distribution - remain rare, in place at only 24% of organizations. Globally, the report identifies packaging waste and poor EoL planning as major unresolved challenges at the distribution site level. Both of those issues are targeted in the Bio4HUMAN project, whose goal is to reduce waste and identify suitable EoL solutions technologies. From the case studies, significant emissions arise from products like tarpaulins and Super Cereal Plus due to material production, EoL management, and international distribution as shown in for tarpaulins sent to Mozambique in Figure 4.

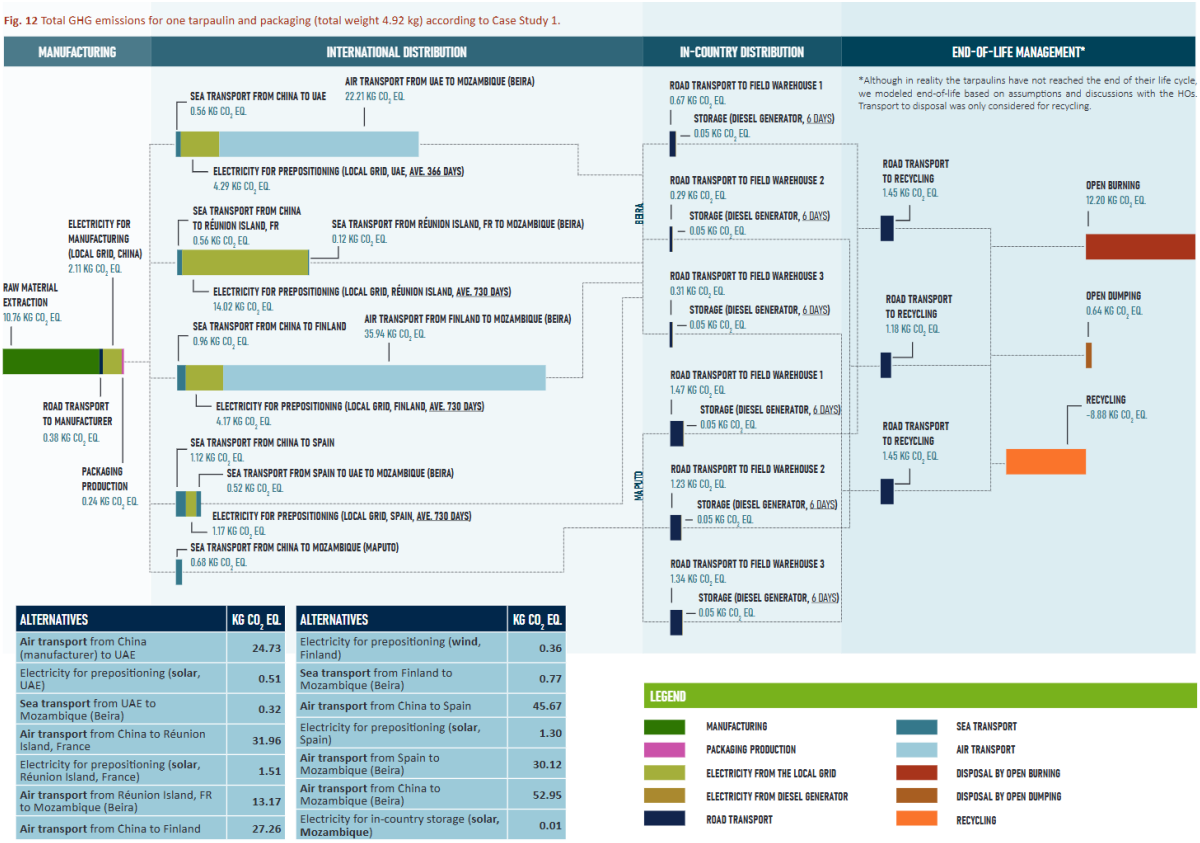


Figure 4 GHG emissions for one tarpaulin to be transported in Mozambique (from WREC/KLU (2024))

Van Kempen et al. (2016) conclude that locally produced stainless steel kitchen sets not only perform better environmentally but also score higher on social and cost indicators for transport. Regarding production costs, manufacturing locally can be more expensive than producing in India. However, local sourcing helps reduce transport-related emissions and supports regional economies. Indeed, the main hotspots in international supply chains include international transportation, the use of plastics and metals, labour risks and associated economic costs.

The table below summarizes the results from local and international production for each assessment method.

Table 2 Hotspots identified in the Van Kempen et al. (2016) study

Assessment method	International (India)	Local (Kenya)
LCA	3923 kgCO_2eq with 1 ton production phase: 97% impacts climate change mainly due to electricity consumption	363 kgCO_2eq with 1 ton production phase: 69%, less energy, higher efficiency, less waste
LCC	US$18.34 production and average of US$4 for transport = US$22 in total per product	US$23.1 production and average of US$2 for transport = US$25 in total per product
S-LCA	Global score for workers, local community and society stakeholder groups of 3.78 (worst = 5)	Global score for workers, local community and society stakeholder groups of 3.23 (worst = 5)

To summarise the findings from all four quantitative studies, **transport and logistics** (especially fuel use and long-distance shipping) are the most common hotspots, while procurement decisions (origin of goods, material choice, production method) drive most upstream impacts. **Waste management and EoL** planning are poorly developed but represent long-term environmental liabilities and decentralized, renewable-powered production and local sourcing are consistently highlighted as effective strategies for impact reduction.

D. Challenges and best practices

Conducting environmental assessments in humanitarian settings faces numerous challenges due to both structural and contextual constraints highlighted in these studies.

- A primary barrier is the **lack of institutional integration of environmental sustainability**, as environmental considerations are often deprioritized in favour of urgent life-saving objectives and are not embedded in funding mechanisms or program design (Brangeon & Crowley, 2020; Anjomshoae et al., 2023).
- Another major issue is the **limited availability of reliable, context-specific data -** especially regarding fuel use, waste generation, and materials—which hampers accurate LCA modelling (Berggren, 2020; WREC/KLU, 2024).
- Many organizations also face a **shortage of technical expertise in LCA**, carbon accounting, or environmental metrics, particularly among logistics and procurement staff (WREC/KLU, 2024).
- The **time-sensitive** nature of emergency response further limits opportunities to plan and conduct assessments, while rapidly changing field conditions also make it difficult to establish stable system boundaries or inventory data (Berggren, 2020).
- Finally, there is a **lack of standardized tools and frameworks** for simultaneously assessing environmental, social, and economic impacts, making it difficult to operationalize sustainability in a holistic way (Van Kempen et al., 2016; Anjomshoae et al., 2023)

To address the multiple challenges, the literature highlights a range of best practices, both institutional and operational. At the strategic level, Brangeon & Crowley (2020) recommend mainstreaming environmental screening tools like NEAT+ into project design and funding processes and embedding environmental requirements in donor templates. To build technical capacity, WREC/KLU (2024) suggest **training** logistics and procurement staff in environmental measurement and circularity, supported using practical tools such as reverse logistics feasibility checklists, waste audit forms, and carbon accounting dashboards. They also encourage collective action through networks like WREC, which unites over 280 organizations around shared sustainability goals. In the field, Berggren (2020) calls for simplified, modular LCA methods that can work with partial or estimated data in dynamic response settings, alongside internal guidance and environmental checklists. Handler et al. (2024) illustrate the benefits of decentralized, solar-

powered local manufacturing using recycled materials, reducing both emissions and logistical complexity. For more systemic sustainability evaluation, Van Kempen et al. (2016) advocate for adopting LCSA approaches to capture environmental, social, and cost trade-offs, and emphasize local sourcing as a strategy to reduce upstream impact. On the data front, several studies highlight the need to establish standardized environmental reporting systems, improve access to **location-specific** life cycle inventory **data**, and promote cross-organizational data sharing to reduce redundancy and improve consistency (Berggren, 2020; Handler et al., 2024; Anjomshoae et al., 2023; WREC/KLU, 2024). These best practices collectively aim to make environmental assessment more feasible, actionable, and embedded in humanitarian operations.

III. Methodology

To perform a hotspot analysis of the solutions identified in WP4, the impacts were calculated with LCIA methodologies with SimaPro LCA software. The processes were mainly modelled during T5.1 with the ecoinvent 3.10 database and literature reviews. To perform the work necessary for this deliverable, models were implemented in the software by WeLOOP. The scopes of each model were adjusted to ensure consistency between the analyses. Using SimaPro and international impact assessment methodologies (e.g., Impact World+, Environmental Footprint (EF) 3.1), hotspot analyses were performed on 1 kg of each material in line with the PEF methodology. The procedure first involved identifying the impact categories that contribute to 80% of the overall impacts, and then, life cycle stages, processes, and elementary flows associated with these impact categories were identified.

The analysis considered the EoL stage, given that the aim of the project is to reduce these impacts. Regarding biobased item solutions, at the end of their life, they do not solely generate waste but can also deliver valuable co-products, such as fertilizers. For example, composting or anaerobic digestion of biobased materials can generate nutrient-rich products that can substitute conventional fertilizers. Within LCA, this substitution is accounted for as an “avoided impact,” since the production of synthetic fertilizers is both resource and energy intensive. Using the EF3.1 method, allocation of benefits from EoL treatment solutions is associated to these avoided impacts, measured across impact categories such as Climate Change or Resource Use and then combined into a single score to show the overall environmental benefit. In this way, fertilizer substitution helps demonstrate how biobased products can lower the environmental footprint compared to fossil-based options.

Different methods can provide information on a wide range of impact indicators. The following sub-sections detail which indicators were identified as most relevant. After studying those of EF3.1, indicators of other EU projects focusing on bio-based products were investigated. The most relevant and available indicators were adopted for this LCA hotspots analysis.

A. Impact categories in the Environmental Footprint 3.1 (EF3.1) method

The EF3.1 impact categories provide a comprehensive framework to assess the potential environmental consequences associated with products, services, or systems throughout their life cycle. The 16 impacts categories cover a wide range of issues, including climate change, resource use, emissions to air, water, and soil, as well as impacts on ecosystems and human health. By structuring the assessment into distinct categories, EF3.1 ensures consistency, comparability, and transparency in environmental evaluations across different sectors and applications. All the categories are detailed in Annex VIII.C.1. Some were selected for the Bio4HUMAN project based on their relevance to fossil and biotic resources:

- **Climate Change:**
  - *Unit:* $kgCO_2eq$ (Carbon dioxide equivalents)
  - *Short description:* represents the global warming potential associated to greenhouse gas emissions (fossil, biogenic and land use).
  - *Relevance to B4H:* high vulnerability to climate change can cause droughts, floods, food insecurity, and vector-borne diseases directly affecting biotic resources production and endangering populations.
- **Water Use:**
  - *Unit:* m^3-world equivalents
  - *Short description:* reflects on the deprivation of freshwater caused by the process.
  - *Relevance to B4H:* information related to water stress, lack of safe water accessibility, or overuse of local water resources.
- **Resource Use, fossils:**
  - *Unit:* MJ (megajoule)
  - *Short description:* evaluates the amount of fossils resource use, converted into megajoules, fossil fuels having inherent energy.
  - *Relevance to B4H:* plastics of reference scenarios are often fossil-based, opposite to the solution materials. Different electricity mixes can also be reliant on fossils.
- **Land Use:**
  - *Unit:* Pts (points)
  - *Short description:* measures impact on soil properties: erosion resistance, groundwater regeneration, biotic production, and mechanical filtration. To aggregate these factors, the land use results are presented in Pts.
  - *Relevance to B4H:* biotic resource production can have impacts on deforestation, land clearing etc.
- **Ecotoxicity, freshwater:**
  - *Unit:* CTUe (Comparative Toxic Unit)
  - *Short description:* evaluates the direct impacts of toxic substances on freshwater ecosystems like rivers, groundwater reserves etc.

- *Relevance to B4H:* pollution of rivers from wastewater, or urban run-off are to be avoided when choosing materials alternatives.

- **Eutrophication, freshwater:**
  - *Unit:* kg Neq (Nitrogen equivalents)
  - *Short description:* pauses the issues relative to overfertilization of freshwater resulting in ecosystem balance disruption with plant or algae overgrowth, suffocating the surrounding wildlife.
  - *Relevance to B4H:* alteration of biodiversity equilibrium due to pesticides or fertilizing released in environment. It is expected to have more importance for bio-based products due to agriculture activities.

B. Biobased indicators developed in EU projects

1. Indicator identification and selection: methodology

To identify relevant indicators to assess the solutions environmental performance, the partners (UC, ITENE, AIMPLAS, WeLOOP) collected those used and developed in other EU projects, namely ALIGNED, BIORADAR, CALIMERO, and LCA4BIO. Indeed, B4H project has living cooperation with most of these projects that were established in the first year of project running. The templates filled by the partners are presented in Annex VIII.A.

The aim of the ALIGNED[14] *(Aligning life cycle assessment methods and bio-based sectors for improved environmental performance)* project was to develop a harmonised LCA methodological framework to improve the environmental and socio-economic performance of biobased industrial processes. The project is focused on five bio-based sectors: construction, woodworking, textile, pulp and paper, and bio-chemicals, with iterative applications in real industrial case studies.

The CALIMERO[15] project *(Industry Case Studies AnaLysis to Improve Environmental Performance and Sustainability of Bio-based Industrial Processes)* aims to create a common framework for all bio-based industries to evolve. The study focuses on PEF indicators as well as new indicators, proposed by CALIMERO. They mainly cover the same sectors as ALIGNED.

BIORADAR[16] *(Monitoring system of the environmental and social sustainability and circularity of industrial bio-based systems)* is an EU project deployed to help organizations, policymakers and investors have the necessary information to step into a more sustainable, bio-based economic model. Thanks to new indicators and digital monitoring tools that will provide benchmarks and a self-assessment platform, they will be able to gauge the environmental and social impacts of their industrial bio-based systems.

LCA4BIO[17] stands for *Harmonised Life Cycle Assessment methods for sustainable and circular BIO-based systems*. It is an EU project with main objective to develop

[14] https://lca4bioproject.eu/
[15] https://calimeroproject.eu/
[16] https://www.bioradar.org/
[17] https://lca4bioproject.eu/

and validate a new set of improved, harmonized, precise, reliable, and applicable assessment methodologies for evaluating environmental impacts and circularity in biobased systems. These methodologies are to be designed for integration into certification schemes, thereby facilitating the international trade of biobased products and supporting the development of next-generation LCA approaches. This project is based on the indicators of CALIMERO and ALIGNED. After the potential indicators have been detected, most relevant and ready-to-use indicators were selected for future assessment in V. Life cycle impact assessment section.

2. Identified EU project indicators relevant to Bio4HUMAN

The Table 3 regroups all identified indicators in the forementioned European projects and reflects the relevance to Bio4HUMAN's context.

Based on relevance and calculation method availability, four indicators were selected for the hotspots analysis, and they are explained in the following section III.B.2. This table however mentions indicators that could be interesting for future studies on bio-sourced materials, but further methodology development is necessary.

Table 3 Biobased indicators developed in other EU projects, potentially relevant for Bio4HUMAN

Indicator	Methodology	Specific to bio-based sector?	Implemented in SimaPro?	Relevant for Bio4HUMAN ?	EU Project	Level of willingness *(mandatory, recommended or experimental)*
Dynamic assessment of Climate change[1]	GWP100 *(Levasseur and Ventura methods)* GWP500 GTP50 GTP100	YES	NO	YES for Construction material only. Packaging solutions have too short lifetimes	ALIGNED	Experimental
Ecosystem quality -Land Use and Land-Use Change ***(LULUC)***	CF for 6 different future scenarios (RCP26,45 or 85) and time horizons (2050 OR 2100). "*gPAF_2XXX_RCPX X*" Endpoint	YES	YES Use RECIPE and Impact World+ methods	YES for bio-based products impact on biodiversity	ALIGNED	Recommended
Biomass availability	under various circumstances	YES	NO a .csv file for market mix calculation (FAOSTAT data)	YES for bio-based products and geographic availability	ALIGNED	Recommended
Material Circularity Indicator (MCI)	See equations BioRADAR D2.1	NO	Not implemented directly, but it can be modelled	YES to compare reference and bio-based solutions circularity potentials. The ratio of secondary material gives an idea on recycling potential	BIORADAR	Recommended
Cost-weighted-average MCI	See equations BioRADAR D2.1	NO	It cannot be modelled as it is an economic indicator	YES to compare reference and bio-based solutions circularity potentials whilst considering recycling cost differences in LCC	BIORADAR	Recommended
Material Durability Indicator (MDI)	See equations BioRADAR D2.1	NO Specific to polymer packaging	It cannot be modelled as it refers to durability	YES to compare reference and bio-based solutions quality	BIORADAR	Recommended

Indicator	Methodology	Specific to bio-based sector?	Implemented in SimaPro?	Relevant for Bio4HUMAN ?	EU Project	Level of willingness *(mandatory, recommended or experimental)*
Emergy (Em) total amount of available energy needed to produce a given product or service	See equations BioRADAR D2.1	NO	It cannot be modelled as it is not meant for LCA purpose	YES to compare reference and bio-based solutions energy requirements	BIORADAR	Recommended
Circular Economy Performance Indicator (CEPI)	See equations BioRADAR D2.1	NO	Cannot be fully modelled as it refers to different categories	YES to underline the real environmental benefits of bio-based solutions	BIORADAR	Recommended
Plastics physical effect on biota	In IMPACT WORLD + (IW+) V2.1 LCIA method	NO	Use IW+ Method	YES to underline the importance of biodegradable solutions	CALIMERO	Recommended
LILAC (Land-use Impact on Landscape connectivity)	A practical execution guide with step-by-step instructions is in CALIMERO WP5.	YES	NO Full technical documentation of the code will be released at the same time	YES for bio-based products impact on biodiversity and geographic availability	CALIMERO	Experimental
Land use Impact on Particulate matter Removal	under development	NO	NO Currently under development	Maybe to underline additional issues related to bio-based solutions	CALIMERO	Experimental
DyPLCA	With life cycle stages process inputs, it provides a graph of emissions over time	NO	No, Brightway compatible. Section 4 of CALIMERO D3.4 develops how it can be ran. Tool: dyplca.list.lu	YES for Construction material only. Packaging solutions have too short lifetimes	CALIMERO	Recommended

Indicator	Methodology	Specific to bio-based sector?	Implemented in SimaPro?	Relevant for Bio4HUMAN ?	EU Project	Level of willingness *(mandatory, recommended or experimental)*
Material Circularity Indicator MCI	/	NO	NO - web tool Material Circularity Indicator | Ellen MacArthur Foundation	YES to compare reference and bio-based solutions circularity potentials	CALIMERO	Recommended
Longevity	/	NO	NO, available formula	YES, to underline bio-based solutions lifetime differences with reference	CALIMERO	experimental
Cascade factor	/	YES	NO, available formula	YES to assess the utilization of biomass, recycled materials	CALIMERO	experimental
Feedstock intensity	/	NO	NO, available formula	Maybe, to underline bio-based solutions production processes efficiency (C content)	CALIMERO	experimental
Product renewability	/	NO	NO, available formula	YES to foster the renewability of bio-based products	CALIMERO	experimental
Energy intensity	/	NO	NO, available formula	YES to assess the difference in energy requirements between reference and solutions	CALIMERO	experimental
%material circularity	/	NO	CTI module Close the loop indicators	YES to compare reference and bio-based solutions circularity potentials	CALIMERO	experimental
%water circularity	/	NO	CTI module Close the loop indicators	YES to compare reference and bio-based solutions water use	CALIMERO	experimental
On-site water circulation (reuse & recycle)	/	NO	CTI module Close the loop indicators	MAYBE to compare reference and bio-based solutions water use	CALIMERO	experimental
%critical material	/	NO	CTI module - Optimize de loop indicators	NO (could underline problems of reference but electronics are not replaced, and no other critical materials are used)	CALIMERO	experimental

Indicator	Methodology	Specific to bio-based sector?	Implemented in SimaPro?	Relevant for Bio4HUMAN ?	EU Project	Level of willingness *(mandatory, recommended or experimental)*
Nature impact	/	NO	CTI module - Impact of the loop indicators	YES for bio-based products impact on nature	CALIMERO	experimental
Amount of land used (h/year) in a product system	/	NO	Not applicable	YES for bio-based products impact on nature (indicator for global criticality tool)	CALIMERO	experimental
Water Depletion Index (WDI)	/	NO	Not applicable	Maybe to compare bio-based products and reference (indicator for global criticality tool)	CALIMERO	experimental
Production/consumption increase/decrease over the last five years	/	NO	Not applicable	Maybe for bio-based solutions availability (indicator for global criticality tool)	CALIMERO	experimental
Criticality	/	NO	Excel tool of CALIMERO D3.3	Potentially for bio-based solutions availability (also does not considers primary issues for B4H)	CALIMERO	experimental
Uptake and emission of biogenic CO_2	Emission factor of EN 15804 (+1/-1)	YES	YES	YES	Aligned	recommended

3. Selected indicators

This section presents the four selected indicators, additional to those of EF3.1.

Biogenic CO_2 (from ALIGNED, from EN15804+A2 standard) represents the amount of CO_2 that is captured by a bio-based material. Indeed, the resource material (plant, seeds, wool) is constituted of carbon (C), captured from the atmosphere thanks to photosynthesis (Equation 1). This reaction emits oxygen back to the atmosphere and C is integrated to the organic matter in the form of starch. Therefore, one C element in the material corresponds to one molecule of CO_2 taken out of the atmosphere. The biotic resources have then stored CO_2 temporarily. With LCA, we can simulate this CO_2 absorption with a negative output of CO_2 to air, associated to the quantity displayed in Equation 2 and associated to a biogenic carbon absorption. This allows to simulate how bio-based material can temporarily store CO_2 out of the atmosphere.

Equation 1 Photosynthesis chemical reaction, biogenic carbon

$6\ CO_2 + 6\ H_2O \rightarrow C_6H_{12}O_6\ (\text{starch}) + 6\ O_2$

Equation 2 Biogenic CO_2 calculation, based on material carbon content

$$CO_2,b,eq = C_{content} \cdot \frac{M(CO_2)}{M(C)}$$

Where:
-CO_2,b,eq is the quantity of biogenic carbon absorption of a material (kg CO_2 eq/kg)
-$C_{content}$ is the carbon content of the wet material (kg/kg)
- $M(CO_2)$ is the molar mass of CO_2 (44 g/mol)
-M(C) is the molar mass of C (12 g/mol)

This indicator will be studied for the solutions only because the reference materials are mainly fossil-based so their C content is not biogenic. This underlines a potential difference between reference and Bio4HUMAN solution materials.

Plastic effect on biota (from CALIMERO from Impact World +) is an indicator calculated by Impact World + v2.1 impact assessment methodology.[18] Depending on microplastic release in the environment, the methodology assesses impacts of plastic leakage on ecosystem quality in PDF.m^2.yr (Potentially Disappeared Fraction of species, per m² per year). Four factors influence the results:

- Quantity (mass)
- Form (microbead, film fragment, or fibre)
- Release water body (lake, ocean, river, unknown)
- Particulate size (from 1 to 1000 µm)

Data on these factors are entered during modelling of EoL process as emissions to water. This methodology is based on *MarILCA characterization factors for*

[18] IMPACT World+ - Version 2.0.1

microplastic impacts in life cycle assessment: Physical effects on biota from emissions to aquatic environments paper of Corella-Puertas et al. (2023).[19]
This indicator is selected because it will underline the issues associated with lack of plastic waste management.

Ecosystem quality (from ALIGNED from Impact World +) is also part of Impact world+ v2.1. It is an endpoint indicator which aggregates into damages on ecosystem quality (endpoint) the impacts of climate change, fisheries, freshwater transformation, ionizing radiations, land occupation and transformation, marine water transformation, photochemical ozone formation, plastic effect on biota, terrestrial transformation, water pollution and availability (midpoint categories). It adds another dimension to the impact categories assessed with EF3.1. and displays how biodiversity can be affected by the fossil-based or bio-based materials. The latter are reliant on ecosystem viability, so this indicator was selected.

The **Material Durability Indicator (MDI)** (from BIORADAR from Mesa et al. (2020) [20]) is intended to capture the durability aspect of materials, encompassing their mechanical and chemical durability as well as their associated environmental impact. While the indicator is originally designed for polymer-based materials, it can be applicable to any material if reference values are adapted. However, MDI will not be evaluated in the scope of this deliverable for building insulation materials for methodological reasons, as this indicator is meant for plastic-based material and the parameters do not take into account thermal insulation properties.

MDI is calculated from eight sub-indicators:

- Chemical durability is covered by flammability resistance, resistance to UV radiation, to water, and to organic solvents
- Mechanical durability is covered by yield strength and fatigue strength
- Environmental impact is represented by Climate Change and Cumulative energy demand (methodology implemented in SimaPro) results per kg of material

In the end, MDI leads to a value of [1;400]. The higher the MDI value, the better the material durability, with optimised chemical and mechanical properties associated with lower environmental impacts.

Criticality (from CALIMERO) is assessed qualitatively in section VI.D. because the introduction of new materials will imply a change in the Humanitarian Aid (HA) supply chain, the probability of a supply disruption of a raw material and the vulnerability of HA to the latter disruption needs to be assessed[21]. A raw material is “critical” if the production is monopolised by a specific region or company, for instance. If this region presents economic instability and is accompanied by other

[19] MarILCA characterization factors for microplastic impacts in life cycle assessment: Physical effects on biota from emissions to aquatic environments
[20] Developing an indicator for material selection based on durability and environmental footprint: A Circular Economy perspective - ScienceDirect
[21] Glöser S, Tercero Espinoza L, Gandenberger C, Faulstich M (2015) Raw material criticality in the context of classical risk assessment. https://doi.org/10.1016/j.resourpol.2014.12.003

concerning factors such as high demand, then the criticality is even higher[22]. This can be of high relevance to the selected locations of Bio4HUMAN.

IV. Inventory

A. Modification of D5.1 inventories

The inventories for solutions and reference scenario were developed in the scope of task T5.1 and its D5.1. and are available in the Annex 1 of D5.1. However, during modelling and impact assessment, work on system boundaries and assumptions homogenisation was performed. Therefore, Annex VIII.B presents the inventories that have been updated or modified for D5.2, compared to D5.1. Among assumptions considered:

Production and composition:

- No site-specific data were considered in this deliverable for simplification and due to lack of specific data for the solution and reference materials production process, as described in D5.1.
- Process material loss (scraps) is considered thrown away under the same conditions as the final product. For instance, waste from PLA bottle production is modelled as industrially composted, just as the bottle. No credits are associated with process scraps EoL.
- Even though multiple PLA processes are analysed (PLA from sugarcane, maize, biowaste and fruit biowaste), PLA produced from maize is used by default for each PLA containing materials during hotspot analysis.
- Difference in regionality is modelled within the materials production and EoL. Three localisations are considered: global (GLO), the DRC or SS. Changes occur in the electricity and heat consumption datasets.

Distribution and Use:

- Distribution phase is considered within generic data (market data).
- Use phase does not have any impact as no maintenance is required for the materials studied.

EoL treatment:

- Biogenic carbon (C) was accounted for by assuming that, after 100 years of composting, 10% of the stored carbon is released to the atmosphere, equally split between CO_2 and CH_4[23]. To avoid underestimation of CH_4 emissions in the ecoinvent database, the EoL biogenic emissions were removed from the original inventories and reintroduced using the calculated values based on the considered carbon degradation (characterisation factor for biogenic methane: 29.8 $kgCO_2$ eq). It was further assumed that no gas flaring occurs in biodegradable waste treatment facilities (including home and industrial composting) within the HA context of the studied countries (the DRC and SS).

[22] Schrijvers D, Hool A, Blengini GA, et al. (2020) A review of methods and data to determine raw material criticality. https://doi.org/10.1016/j.resconrec.2019.104617
[23] 20230525_GDBAT_Phase2-ACV_Rapport-avec-revue_VF.pdf

Indeed, waste treatment facilities are often very basic in these locations, even though landfills are subjected to methane production, generated in anaerobic conditions, i.e. in absence of oxygen. Compost is an aerobic process if correctly ventilated and could produce less oxygen than the aforementioned scenario.

- Degradation of biogenic C of ecoinvent datasets was not considered. Only the carbon emissions of the scenario mentioned before.
- Sheep wool degradation is particularly low. Indeed, sheep wool is composed of 5% of water and 95% keratin which is resistant to degradation[24]. Under specific composting conditions, wool can degrade and release N, K, P and S compounds (e.g., ammonia or sulphides) [25] . In anaerobic conditions, degradation is limited but emits methane and other greenhouse gases. To represent sheep wool slow degradation compared to most plant-based materials: all carbon is considered to stay in the ground at EoL.
- For solutions that are home composted and open burnt, collection at EoL (transportation to waste treatment facility) was included to avoid underestimation, but there is a high probability that it will not occur. Collection at EoL was systematically considered for landfill (in reference scenario) and industrial composting.
- Packaging units of disposable compostable pads is compostable and composted.

EoL of coproducts and credits:

- When necessary, heat/electricity recovery and fertilising credits are modelled in parallel of the producing process. When not in the D5.1 model, credits for electricity and heat correspond to the net energy production specified in the treatment process of the incineration process.
- EoL credits are considered apart from the EF3.1 LCIA and are not part of the inventories.
- Credits for soil nutrition correspond to an average compost composition after 6 months (D5.1, Annex 1, Table 14), without stirring. This is valid for products where the precise composition of N, P, or K is not known: natural rubber in biodegradable tape, organic disposable pads).

Credits calculation details are presented in VIII.B.2.f) and VIII.B.3.

Dataset modification:

- Cardboard open burning: “Waste paperboard {GLO}| treatment of waste paperboard, open burning | Cut-off, U” process indicates an initial mercury Hg content of 39.61mg/kg. This mercury is emitted back into the air during open burning, which induces high impacts on Human Toxicity (non-cancerous). However, the European regulation suggests a limited amount of 0.3mg/kg, even though Elmas, G & Çınar, G (2018) have measured some Hg

[24] https://landreclamationjournal.usamv.ro/pdf/2022/Art57.pdf
[25] (PDF) The Potential for Hydrolysed Sheep Wool as a Sustainable Source of Fertiliser for Irish Agriculture

contaminations up to 3.8mg/kg in paperboards[26]. This dataset was adapted for this article with an initial Hg content of 0.3mg/kg.

B. End-of-Life scenarios clarifications

1. Reference items

As previously mentioned, in D5.1, it was seen that in the reference scenario, about 10% of the waste streams are managed in the studied countries, the remaining mostly being open dumped. However, in this deliverable, for the purposes of life cycle modelling, the openly dumped fraction has been treated as if it were open burnt.

This modelling choice stems from a key limitation in the ecoinvent database and the EF3.1 method: the environmental impacts associated with open dumping are significantly underestimated. As illustrated in Figure 5, the impacts of open dumping are equivalent to those of sanitary and unsanitary landfills. A further analysis shows that landfill is associated with higher impacts because of infrastructure and machine operation. In contrast, the specific and critical environmental consequences of open dumping (such as plastic leakage through wind or water dispersion) are not adequately captured in EF3.1.

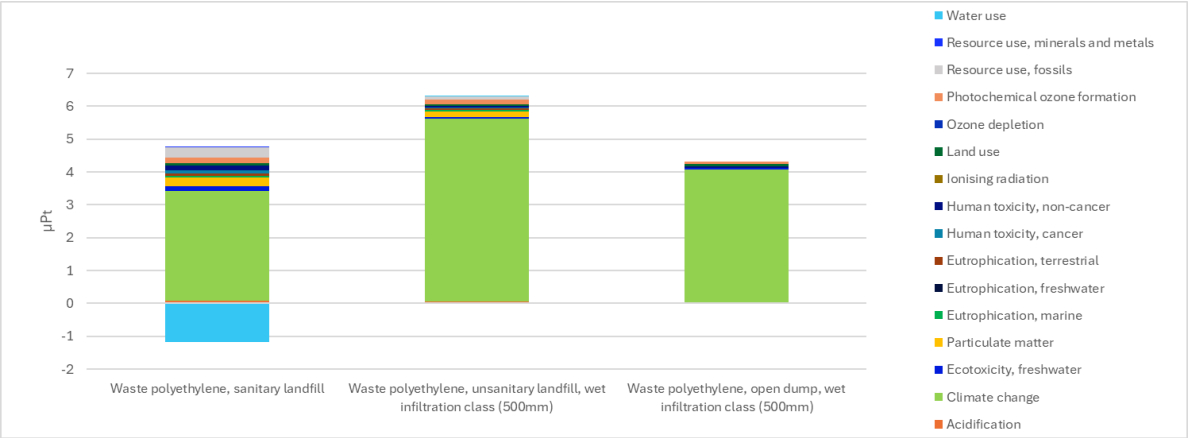


Figure 5 Analysis of open dumping impacts, compared to sanitary an unsanitary landfill. Example of PE, treated in the DRC, single score

To address this gap and avoid inconsistencies in the comparative analysis between reference and alternative solutions with EF 3.1, unmanaged waste has been modelled as open burning. This modelling assumption is grounded in two considerations:

1. Open dumping and open burning frequently co-occur in the studied contexts, making this assumption contextually plausible.

[26] Toxic metals in paper and paperboard food packagings: BioResources

2. The EF3.1 method provides a more detailed and representative characterisation of the environmental impacts of open burning, especially regarding air pollution and climate change indicators.

It must be noted that open burning is not related to the same environmental impacts as open dumping (Cf. Figure 6 and Figure 7). Open dumping is particularly associated with long-term plastic pollution and degradation in natural environments, whereas open burning is characterised by high emissions of Particulate matter, greenhouse gases and other air pollutants. Therefore, the use of open burning as a proxy for open dumping should be seen as a modelling compromise, and handled with care, i.e. a way to partially reflect the severity of unmanaged waste impacts within the constraints of the current LCIA methodology.

The significance of the impacts related to plastic debris is further highlighted in this report in parallel to the EF3.1 results to complete the hotspots analysis. Indeed, only Impact World+ v.2 methodology assesses these impacts with “Plastic effect on biota” indicator, studied in sections V.B.2.k)(1) and V.B.3.j)(1).

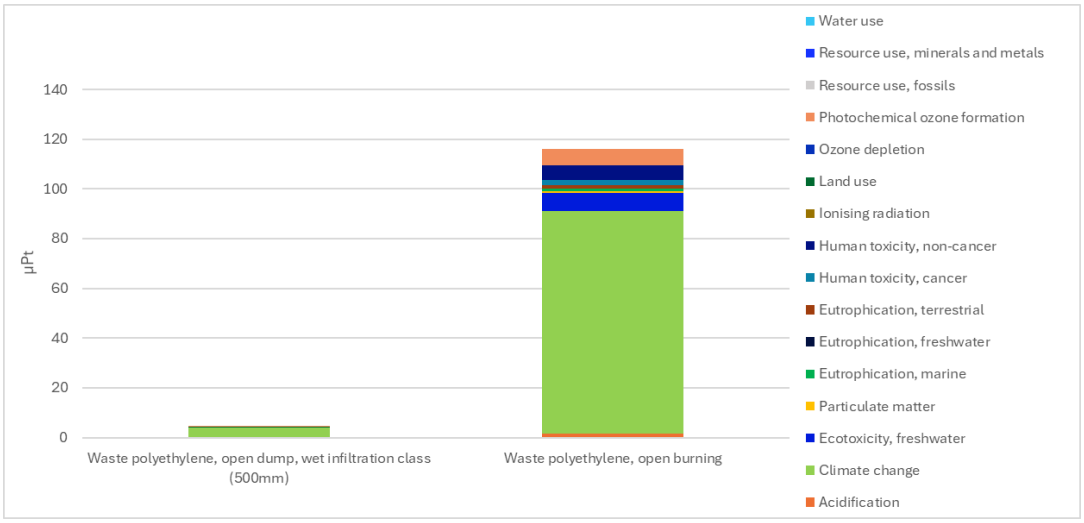


Figure 6 Analysis of open dumping impacts, compared to open burning. Example of PE waste, treated in DRC, single score.

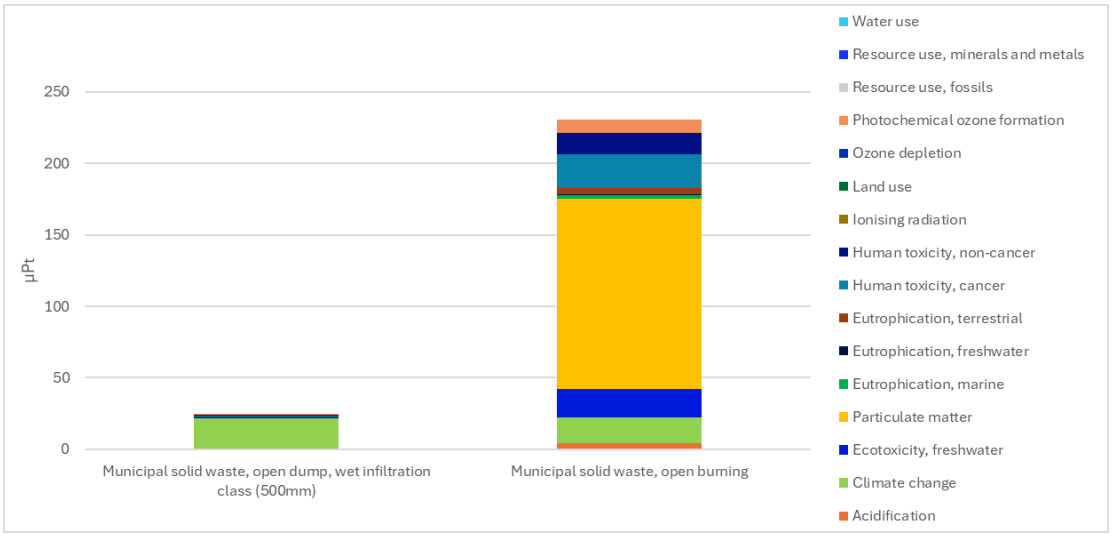


Figure 7 Analysis of open dumping impacts, compared to open burning. Example of Municipal Solid waste (multi compound material), treated in DRC, single score.

This compromise is further justified by supplementary analysis using the ReCiPe 2016 (H) LCIA methodology and endpoint indicators. As shown in Figure 8, biodiversity impacts for municipal solid waste are similar between the open dump and open burn scenarios, reinforcing the environmental significance of both waste mismanagement pathways. Details on the methodology are available in the Annex VIII.C.2.

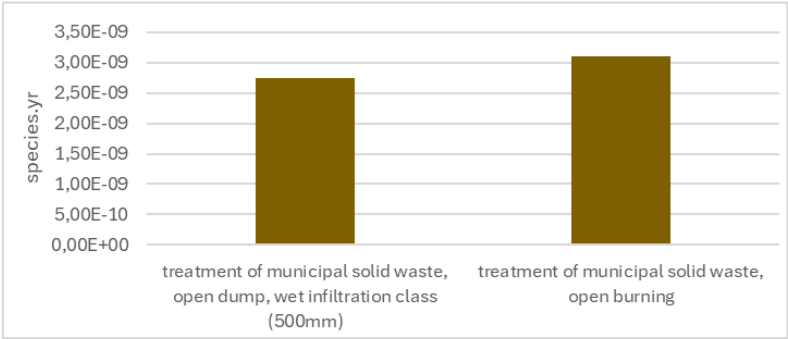


Figure 8 Analysis of open dumping impacts, compared to open burning. Example of municipal solid waste, treated in DRC, ReCiPe 2016 Endpoint (H): Impact on Ecosystems.

2. Solution items

For compostable solutions (home or industrial), carbon content within the products was set to disintegrate as suggested by FCBA in the scope of GDBAT project[27], as described in the assumptions in part IV.A. 10% of the stored carbon is released to the atmosphere, equally split between CO_2 and CH_4. Wool composting does not emit C back into the atmosphere because C in sheep wool is mineral and not organic, opposite to all other solution materials as said in the assumptions.

For open burning, 100% of biogenic C is emitted back into the atmosphere. Around 99,99% is emitted as CO_2 and the remaining as biogenic CH_4. The proportion

[27] 20230525_GDBAT_Phase2-ACV_Rapport-avec-revue_VF.pdf

between CO_2 and CH_4 were retrieved from ecoinvent waste treatments by open burning datasets. The ecoinvent datasets were adapted depending on material initial carbon content.

In the following table, the carbon content of each solution material is provided. The latter is associated to a biogenic carbon absorption. This allows simulation of how bio-based material can temporarily store CO_2 out of the atmosphere. This Table 4 also summarizes the emissions at EoL. In this table, biogenic CH_4 emissions are associated to a characterisation factor of 29.8kgCO_2eq, as suggested by EN15804+A2 methodology, which considers biogenic CO_2 in the assessment results.

As an example of the information that it is included on the table, for the PLA bottle, the carbon content of 1kg of dry mass is 0.500 kg of C, which comes from the biogenic CO_2 equivalent absorption of 1.833 kg of CO_2,b eq. The following equation allows to visualize the calculation:

Equation 3. Example of the calculation of the Biogenic CO_2 equivalents absorption for PLA bottle for oil and water

$$kg\ CO2b,eq = \frac{0.5\ kg(C,b)}{0.0120kg\ C/1mol\ C} * \frac{1\ mol\ CO2}{1\ mol\ C} * \frac{0.044\ kg\ CO2}{1\ mol\ CO2} = 1.83\ kg\ CO2,b\ eq\ (absorption)$$

In the case of the industrial composting of PLA bottle, the biogenic emissions are split into carbon dioxide (0.92 kg CO_2,b) and methane emissions (0.033 kg CH_4,b). To convert the methane emissions into CO_2 equivalent, the 0.033 kg CH_4 must be multiplied by the characterization factor mentioned above, 29.8 kg CO_2 eq/kg CH_4. The resulting value can then be added to the CO_2 emissions to obtain the total CO_2 equivalent emissions.

Table 4 Biogenic carbon (C,b) of solution materials and emissions at solution EoL[28]

Solution material (1kg)	Carbon content, biogenic	Dry Mass	Biogenic CO_2, equivalents absorption	**EoL process**	Biogenic CO_2 emissions	Biogenic CH_4 emissions	Biogenic CO_2, equivalent emissions
	kg(C,b)/ kg(DM)	**DM (kg)**	**CO_2,b, eq (kg)**		**CO_2,b emissions (kg)**	**CH_4,b emissions (kg)**	**CO_2,b eq emissions (kg)**
PLA bottle for oil and water	0,500	1	1,833	Industrial compost	**0,091**	**0,033**	**1,09**
PHBV bottle for oil and water	0,599	1	2,196	Home compost	**0,109**	**0,039**	**1,30**
Compostable sachet for RUTF	0,410	1	1,505	Home compost	**0,752**	**0,027**	**0,89**
PLA + natural adhesive	0,621	1	2,275	Home compost	**0,113**	**0,041**	**1,35**
Biodegradable laminating film	0,500	1	1,833	Industrial compost	**0,916**	**0,033**	**1,09**
Mycelium protective material	0,327	1	1,200	Compost	**0,060**	**0,022**	**0,71**

[28] kg(C,b)/kg(DM) were retrieved from ecoinvent 3.10 or calculated manually based on polymer chemical formula.

Solution material (1kg)	Carbon content, biogenic	Dry Mass	Biogenic CO_2, equivalents absorption	EoL process	Biogenic CO_2 emissions	Biogenic CH_4 emissions	Biogenic CO_2, equivalent emissions
	kg(C,b)/ kg(DM)	**DM (kg)**	**CO_2,b, eq (kg)**		**CO_2,b emissions (kg)**	**CH_4,b emissions (kg)**	**CO_2,b eq emissions (kg)**
Disposable bag from renewable sources	0,625	1	2,292	Industrial compost	**0,114**	**0,041**	**1,36**
Foams for insulation	0,691	1	2,533	Open burning	**2,533**	**6,61E-09**	**2,53**
Wool Insulation material	0,505	0,87	1,610	Home compost	**0,000**	**0,000**	**0,00**
Bio-based insulation	0,459	0,95	1,598	Open burning	**1,598**	**6,79E-09**	**1,60**
Cellulose-based insulation	0,444	1	1,628	Open burning	**1,628**	**4,25E-09**	**1,63**
Organic disposable Sanitary pads with wings	0,474	0,98	1,703	Home compost	**0,085**	**0,031**	**1,01**
Monofilaments Mosquito net	0,500	1	1,833	Industrial compost	**0,091**	**0,033**	**1,09**

C. Energy: electricity and heat

In the following analysis, all energy inputs (i.e., electricity and heat) in developed inventories were modelled with a global market dataset (GLO), or with RER region datasets if process was confirmed to occur in Europe specifically.

However, as a sensitivity analysis, it could be interesting to explore whether electricity and heat local consumption in the DRC and SS might lead to other impacts. The electricity grid mix in the DRC is primarily based on hydraulic electricity[29], whereas SS relies mainly on oil[30]. The following inventories for both countries' energy consumption were modelled:

Table 5 Electricity grid mix of DRC, ZA = South Africa, RoW = Rest-of-World

Electricity source (DRC grid mix)	Quantity (%)	dataset
Hydro (run-of-river)[31]	99.56	Electricity, high voltage {ZA}| electricity production, hydro, run-of-river | Cut-off, U
Diesel	0.2	Electricity, high voltage {RoW}| heat and power co-generation, diesel, 200kW electrical, SCR-NOx reduction | Cut-off, U
Solar	0.2	Electricity, high voltage {RoW}| electricity production, solar tower power plant, 20 MW | Cut-off, U
Oil	0.04	Electricity, high voltage {RoW}| electricity production, oil | Cut-off, U

[29] Democratic Republic of the Congo - Countries & Regions - IEA
[30] South Sudan - Countries & Regions - IEA
[31] https://www.hydropower.org/region-profiles/africa

Table 6 Heat production mix of DRC

Heat source (DRC mix)	Quantity (%)	dataset
Oil	4.1	Heat, district or industrial, other than natural gas {RoW}| heat and power co-generation, oil | Cut-off, U
Biogas	95.9	Heat, central or small-scale, other than natural gas {RoW}| heat and power co-generation, biogas, gas engine | Cut-off, U

Table 7 Electricity grid mix of SS

Electricity source (SS grid mix)	Quantity (%)	dataset
Diesel	93.5	Electricity, high voltage {RoW}| heat and power co-generation, diesel, 200kW electrical, SCR-NOx reduction | Cut-off, U
Solar	6.5	Electricity, high voltage {RoW}| electricity production, solar tower power plant, 20 MW | Cut-off, U

Table 8 Heat production mix of SS

Heat source (SS mix)	Quantity (%)	dataset
Oil	73.7	Heat, district or industrial, other than natural gas {RoW}| heat and power co-generation, oil | Cut-off, U
Biogas	26.3	Heat, central or small-scale, other than natural gas {RoW}| heat and power co-generation, biogas, gas engine | Cut-off, U

V. Life cycle impact assessment

A. Results

This section presents the impact results for the previously selected impact categories and indicators. The results presented reflect potential environmental impacts, assuming that the emissions follow the characterisation models and impact pathways established by the EF 3.1 methodology. Besides, the inventories of D5.1 were developed based on multiple hypotheses, and the LCIA results only capture that fraction of the total environmental load that corresponds to the chosen functional unit (relative approach). LCIA results are relative expressions only and do not predict actual impacts, exceeding thresholds, safety margins, or risks. The inventory analysis results are linked to specific environmental midpoint impact categories (e.g. global warming, acidification, etc.). In this report, the overall impact assessment results per unit of analysis were calculated, excluding long-term emissions (emissions occurring after 100 years).

This study outlined in D5.2 is carried out to include all EF impact categories listed in III.A. As explained in part III, the procedure first involved identifying the impact categories that contribute to 80% of the overall impacts. Then, the origin of these impacts is identified in the tables and the single score and Climate Change results figures. Additionally, the identified relevant EF3.1 impact categories will be assessed even if not responsible of 80% of overall impacts.

The results of the LCIA are calculated for the following reference flow: 1kg of material. The study is cradle-to-grave and focuses on the materials of the solutions as well as the associated potentially replaced reference items.

B. Materials hotspots analysis

1. Plastic transformation processes

In the following analyses, the studied materials are either blow-moulded, extruded, co-extruded, or injection-moulded as made with plastics. In the hotspots analysis, it is seen that the transformation of plastic is often a hotspot (i.e. contributing to the first 80% of impact results). Therefore, this section is dedicated to the study of the different transformation processes mentioned above. Figure 9 shows that the highest impacts in a single score of each process come from Climate Change, Resource Use, fossil fuels, Particulate matter, Acidification, and Photochemical ozone formation.

When examining the blow moulding process, for instance, as shown in Figure 10, it becomes evident that the main impacts stem from electricity consumption. This trend is also observed in the other transformation processes.

Another interesting point is that each transformation process has an impact on land use (up to 24 Land Use Pt for blow moulding). Figure 10 pinpoints that cardboard used for raw material packaging is responsible for such impacts. Therefore, in the following hotspot analysis, the plastic transformation process will appear as a contributor to land-use impacts, even though it is very low (0,3 to 2% contribution to total single score).

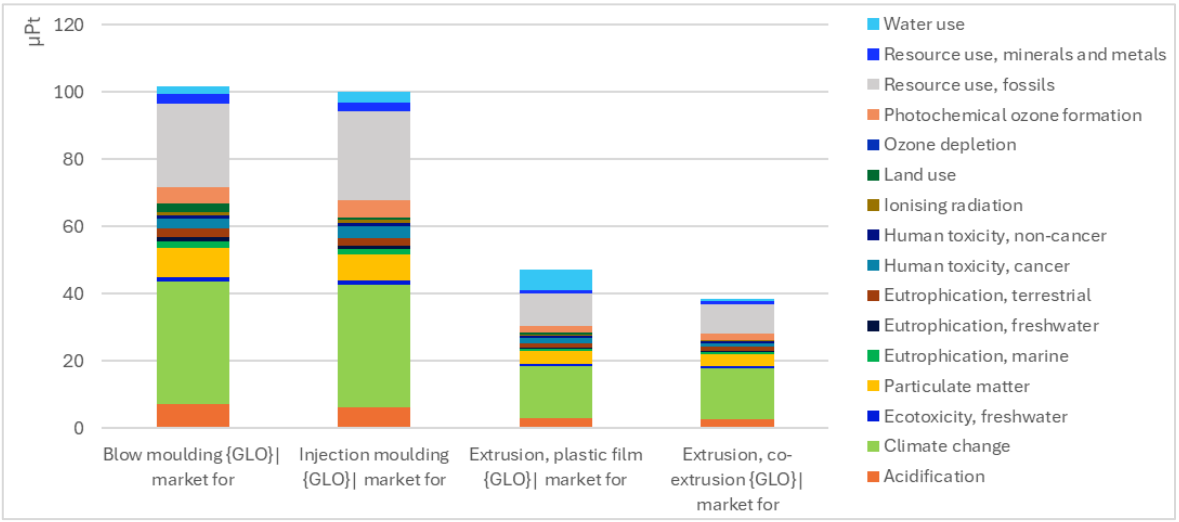


Figure 9 Plastic transformation processes impacts for 1kg of transformed plastic, Single score EF3.1

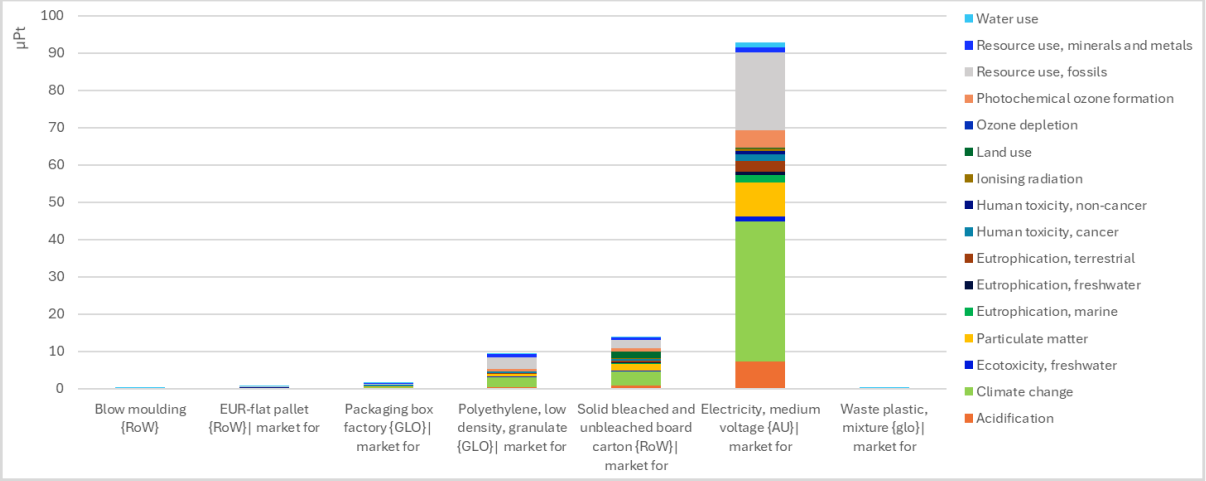


Figure 10 Blow moulding, plastic transformation process for 1kg of blow-moulded plastic, Single score EF3.1

To conclude, **when the transformation process is a hotspot, electricity use is the primary reason**. Therefore, modifying the grid mix could influence the environmental impacts of the final product. This conclusion underlines the importance of geography in material sourcing. A plastic product manufactured in France (mainly using nuclear energy[32]) will be less impactful than the same product manufactured in Germany (mainly using fossil energy[33]). Similarly, if the plastics were to be manufactured in the countries of interest, namely the DRC and SS, a significant difference could also be observed due to grid mix differences as DRC use mainly hydraulic power and SS oil, as outlined in IV.C and VI.A.

2. Reference materials

a) Oil container materials

HDPE jerrycans containing oil for the Food kit are manufactured by blow moulding. Here, the impacts of 1kg of products are studied.

The LCIA results with EF3.1 methodology highlight five hotspots, marked in orange:

Table 9 Oil container LCIA, impact categories hotspots and results: HDPE jerrycans, 1 kg

Midpoint impact categories *(EF3.1, hotspots 80%)*	Unit	For 1kg	Contribution (%)	Hotspots, process contribution (80%)
Climate Change	kg CO_2 Eq	7,41E+00	40,44	HDPE > EoL > Blow moulding
Resource Use, fossils	MJ	9,83E+01	24,62	HDPE
Particulate matter	disease incidence	1,94E-07	5,72	HDPE > Blow moulding > EoL
Resource Use, minerals and metals	kg Sb eq	2,37E-05	5,49	HDPE
Photochemical ozone formation	kg NMVOC eq	2,36E-02	5,4	HDPE > Blow moulding > EoL
Ecotoxicity, freshwater	CTUe	4,61E+01	3,05	HDPE > EoL

[32] France - Countries & Regions - IEA
[33] Germany - Countries & Regions - IEA

Midpoint impact categories *(EF3.1, hotspots 80%)*	Unit	For 1kg	Contribution (%)	Hotspots, process contribution (80%)
Water Use	m^3-world eq	1,06E+00	1,54	HDPE > Blow moulding
Land Use	dimension-less (pt)	3,33E+01	0,63	Blow moulding > HDPE
Eutrophication, freshwater	kg P eq	1,45E-04	0,49	HDPE > Blow moulding

From the table above and the graphs below, the most impactful processes are:

- High density polyethylene (HDPE, fossil based) production; dataset based on 2016 data and reviewed in 2021, accurately represents the technology, with low geography representativeness.
- Polyethylene EoL by open burning (see section IV.B.1).
- And plastic transformation by blow moulding (see section V.B.1).

A further analysis of HDPE production demonstrates that its impacts stem from ethylene monomer production, which is responsible for high impacts on Resource Use, fossils, Climate Change, Particulate matter, Resource Use, minerals and metals, and Photochemical ozone formation. The chemical factory is also responsible for Resource Use, minerals and metals.

It can also be noted that EoL is the least impactful step in single score, but in terms of Climate Change, the impact of EoL is higher than the one of blow moulding, due to important emissions of greenhouse gases during open burning.

To conclude, HDPE jerrycans used as oil containers in the food kit have an impact throughout their entire life cycle: from raw material extraction and manufacturing to EoL.

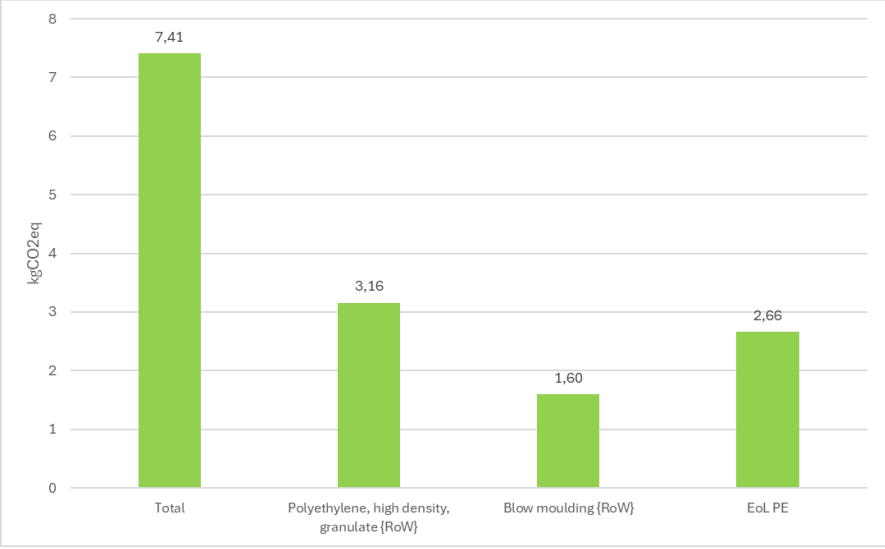


Figure 11 Oil container LCIA, Climate Change results: HDPE jerrycans, 1 kg

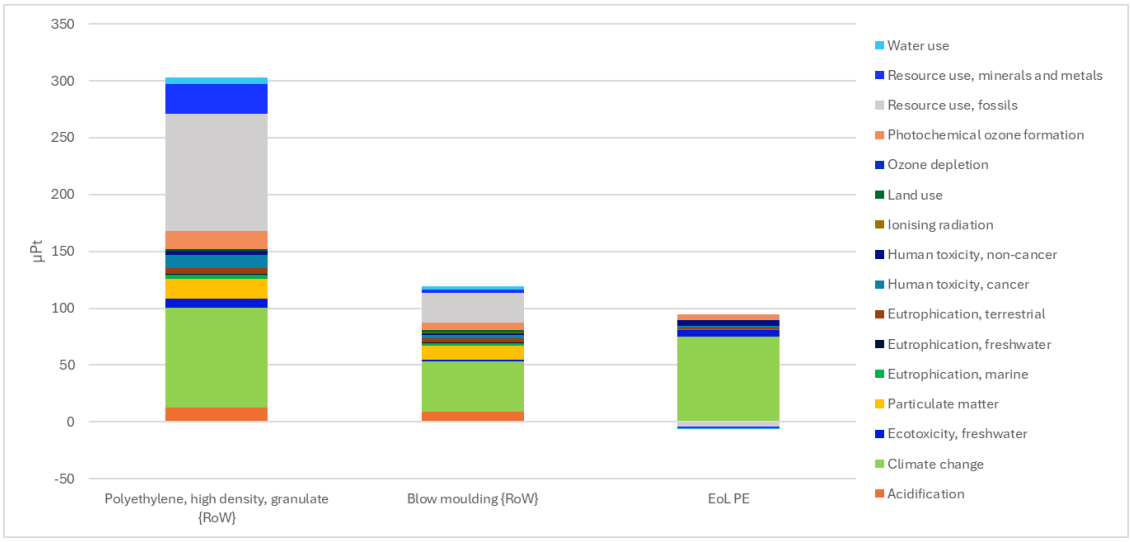


Figure 12 Oil container LCIA, Single score results: HDPE jerrycans, 1 kg

b) Water container materials

Water containers in the WASH kit represents a 10L LDPE containers without logo, manufactured by blow moulding. The impacts of 1kg of products are studied in the following paragraphs.

The LCIA results with EF3.1 methodology highlight five hotspots:

Table 10 Water container LCIA, impact categories hotspots and results: LDPE containers, 1 kg

Midpoint impact categories *(EF3.1, hotspots 80%)*	Unit	For 1kg	Contribution (%)	Hotspots, process contribution (80%)
Climate Change	kg CO_2 Eq	7,31E+00	39,81	LDPE > EoL > Blow moulding
Resource Use, fossils	MJ	9,91E+01	24,78	LDPE
Photochemical ozone formation	kg NMVOC eq	2,53E-02	5,77	LDPE > EoL
Resource Use, minerals and metals	kg Sb eq	2,37E-05	5,49	LDPE
Particulate matter	disease incidence	1,85E-07	5,43	LDPE > Blow moulding
Ecotoxicity, freshwater	CTUe	4,64E+01	3,07	LDPE > EoL
Water Use	m^3 world eq	1,30E+00	1,88	LDPE > Blow moulding
Land Use	dimension-less (pt)	3,32E+01	0,63	Blow moulding > LDPE
Eutrophication, freshwater	kg P eq	1,61E-04	0,55	LDPE > Blow moulding

From the table above and graphs presented in Figure 13 and Figure 14, the most impactful processes are:

- Low-density polyethylene (LDPE, fossil-based) production, dataset based on 2016 data and reviewed in 2021, accurately represent the technology, with low geography representativeness.
- Polyethylene EoL by open burning (see section IV.B.1).

- And plastic transformation by blow moulding (see section V.B.1).

A further analysis of LDPE production demonstrates that its impacts come from ethylene monomer production, as observed for HDPE oil container above. Ethylene is therefore responsible for significant impacts on Resource Use, fossils, Climate Change, Particulate matter, Resource Use, minerals and metals, and Photochemical ozone formation. The chemical factory is also responsible for Resource Use, minerals and metals.

As mentioned for HDPE, EoL is the least impactful step in single score but in terms of Climate Change, the impact of EoL is higher than the one of blow moulding due to significant emissions of greenhouse gases during open burning.

To conclude, LDPE water containers in the WASH kit have a significant impact throughout the entire life cycle: from raw material extraction and manufacturing to EoL.

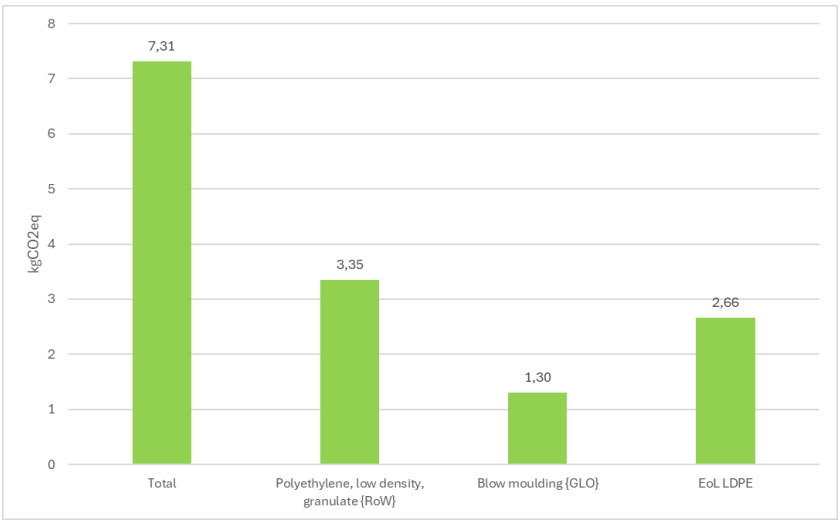


Figure 13 Water container LCIA, Climate Change results: LDPE container, 1 kg

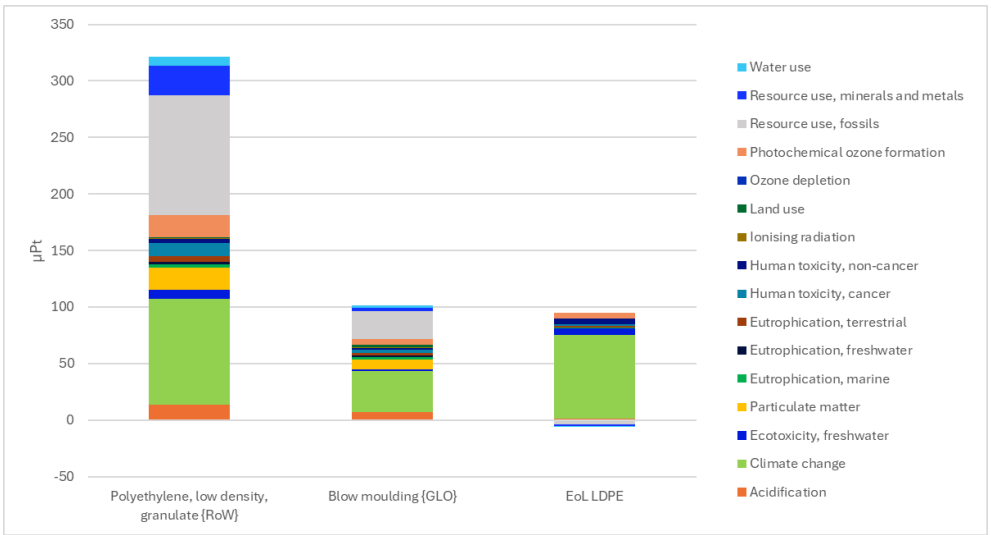


Figure 14 Water container LCIA, Single score results: LDPE container, 1 kg

c) *Pouch for RUTF materials*

To contain Ready-to-use therapeutic foods (RUTF), a multimaterial packaging film is used made with two PE layers metalized PET. The impacts of 1kg of such packaging are studied in the following paragraphs.

The LCIA results with EF3.1 methodology highlight six hotspots:

Table 11 Pouch for RUTF LCIA, impact categories hotspots and results: metalized PET and PE layers, 1 kg

Midpoint impact categories *(EF3.1, hotspots 80%)*	Unit	For 1kg	Contribution (%)	Hotspots, process contribution (80%)
Particulate matter	disease incidence	9,64E-07	24,22	EoL
Climate Change	kg CO_2 Eq	4,75E+00	22,1	PET > LLDPE > EoL
Resource Use, fossils	MJ	8,70E+01	18,6	LLDPE > PET
Human Toxicity, cancer	CTUh	3,02E-08	6,24	EoL > PET
Resource Use, minerals and metals	kg Sb eq	2,88E-05	5,71	PET > LLDPE
Photochemical ozone formation	kg NMVOC eq	2,36E-02	4,62	PET > LLDPE > EoL
Ecotoxicity, freshwater	CTUe	7,58E+01	4,28	EoL > PET
Water Use	m^3 world eq	1,73E+00	2,14	LLDPE > Extrusion > PET
Eutrophication, freshwater	kg P eq	1,60E-04	0,46	EoL > PET > LLDPE
Land Use	dimensionless (pt)	1,35E+01	0,22	LLDPE > PET

From the table above and the graphs presented in Figure 15 and Figure 16, the most impactful processes are:

- EoL by open burning of the multimaterial (municipal solid waste) (see section IV.B.1).
- Linear low-density polyethylene (LLDPE, fossil-based) production; dataset based on 2016 data and reviewed in 2021, accurately represent the technology, with low geography representativeness.
- And polyethylene terephthalate (PET) production (2 layers); dataset based on 2011 data and reviewed in 2021, accurately represent the technology, with low geography representativeness.

An analysis of LLDPE production demonstrates that its impacts come from ethylene monomer production, as observed for LDPE and HDPE above. Ethylene is therefore responsible for significant impacts on Resource Use, fossils, Climate Change, Particulate matter, Resource Use, minerals and metals, and Photochemical ozone formation. The chemical factory is also responsible for Resource Use, minerals and metals.

Moreover, the PET production single score analysis displays similar impact categories associated with terephthalic acid and ethylene synthesis, the monomers used in PET production. To conclude, RUTF packaging in the Food kit is impactful due to the synthesis of raw materials and EoL. Although the EoL contribution to

Climate Change is not as significant as other categories, a single-score analysis reveals that municipal solid waste open burning has an impact on other categories, due to the multi-component composition of the pouch packaging.

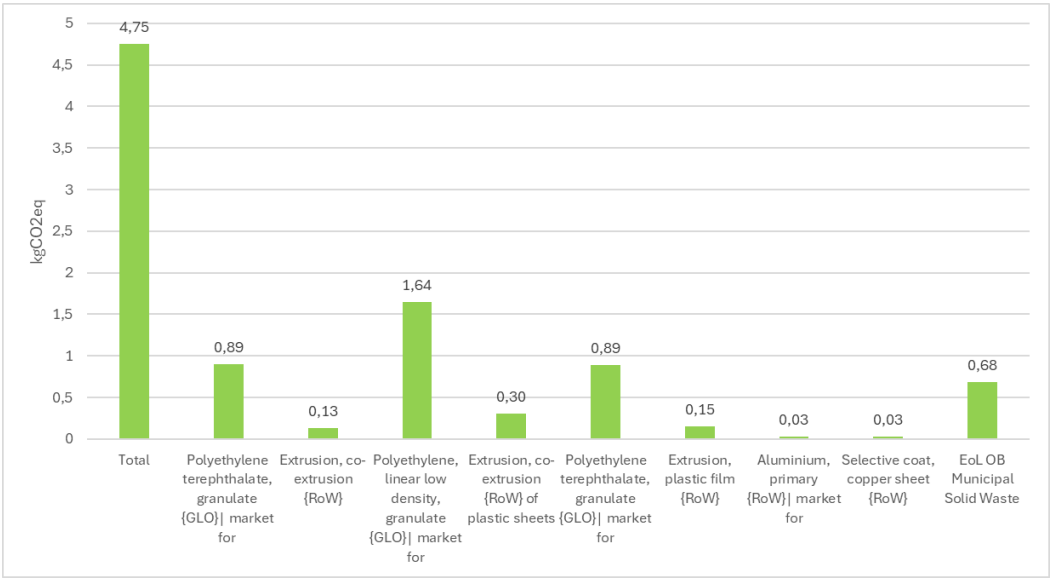


Figure 15 Pouch for RUTF LCIA, damage assessment Climate Change: metalized PET and PE layers, 1 kg

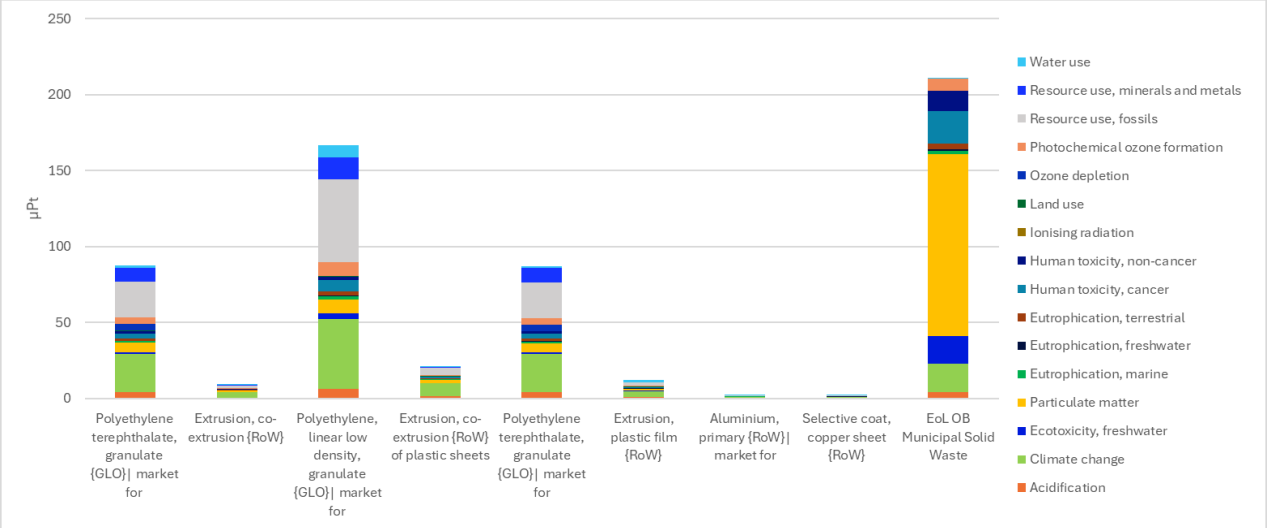


Figure 16 Pouch for RUTF LCIA, Single score: metalized PET and PE layers, 1 kg

d) Bags for primary packaging materials

The items in the kits sometimes need to be enveloped in a primary PE liner and then placed in a secondary packaging: a PP bag. The PE liner provides sufficient strength and airtightness to the PP bag to ensure an adequate packaging quality for different products, such as blankets (NFI kit), dry food items (food kit), seeds (agricultural kit), or cloth material (WASH kit) (See D5.1, Annex 1). More details are available in D5.1, Annex 1 inventories. Different thicknesses are required depending on the product's weight; however, in this case, the thickness has been determined based on the manufacturing process for a bag designed to hold up to 40kg. The

study is conducted per kg; thus, the impacts are approximately the same for thinner bags; PP and PE ratios might differ slightly.

The LCIA results with EF3.1 methodology highlight six hotspots:

Table 12 Bags for primary packaging LCIA, impact categories hotspots and results: PP and PE layers, 1 kg

Midpoint impact categories *(EF3.1, hotspots 80%)*	Unit	For 1kg	Contribution (%)	Hotspots, process contribution (80%)
Climate Change	kg CO_2 eq	6,46E+00	38,55	PP > HDPE > EoL
Resource Use, fossils	MJ	8,91E+01	24,43	PP > HDPE
Photochemical ozone formation	kg NMVOC eq	2,35E-02	5,88	PP > HDPE
Resource Use, minerals and metals	kg Sb eq	2,29E-05	5,81	PP > HDPE
Particulate matter	disease incidence	1,60E-07	5,17	PP > HDPE
Acidification	mol H^+ eq	1,87E-02	4,46	PP > HDPE
Ecotoxicity, freshwater	CTUe	4,61E+01	3,34	PP > HDPE > EoL
Water Use	m^3-world eq	1,70E+00	2,70	PP > HDPE > Extrusion
Land Use	dimensionless (pt)	1,80E+01	0,37	PP > HDPE

From the table above and the graphs presented in Figure 17 and Figure 18, the most impactful processes are:

- Polypropylene (PP, fossil-based) production; dataset based on 2016 data and reviewed in 2021, accurately represents the technology, with low geography representativeness,
- Polyethylene (HDPE) production; dataset based on 2016 data and reviewed in 2021, accurately represents the technology, with low geography representativeness,
- EoL by open burning of the multi material (municipal solid waste) (see section IV.B.1)

Polypropylene production single score analysis displays most impacts associated with propylene synthesis, the monomer for polypropylene production. Propylene is, therefore, responsible for significant impacts on Resource Use, fossils, Climate Change, Resource Use, minerals and metals, Particulate matter, and Photochemical ozone formation.

As mentioned in the previous sections, polyethylene production presents impact coming from ethylene monomer production. It can also be pinpointed that, for bags production, extrusion only contributes to 5% of single score impacts, so plastic transformation impact is negligible overall for this material.

To conclude, primary packaging with PE/PP bags impacts stem from raw materials synthesis, specifically PP and PE.

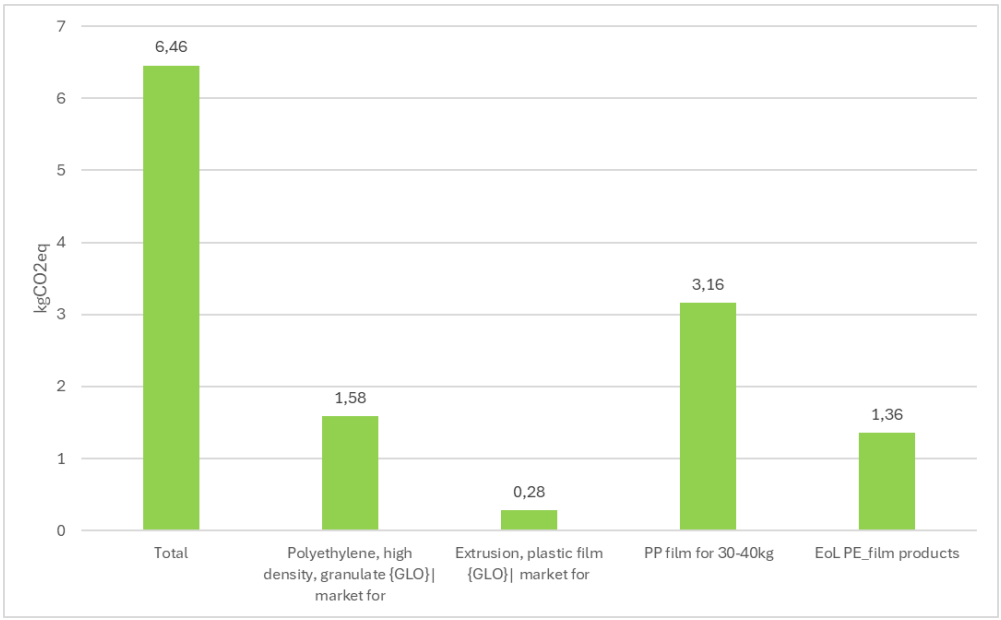


Figure 17 Bags for primary packaging LCIA, damage assessment Climate Change: 1 kg

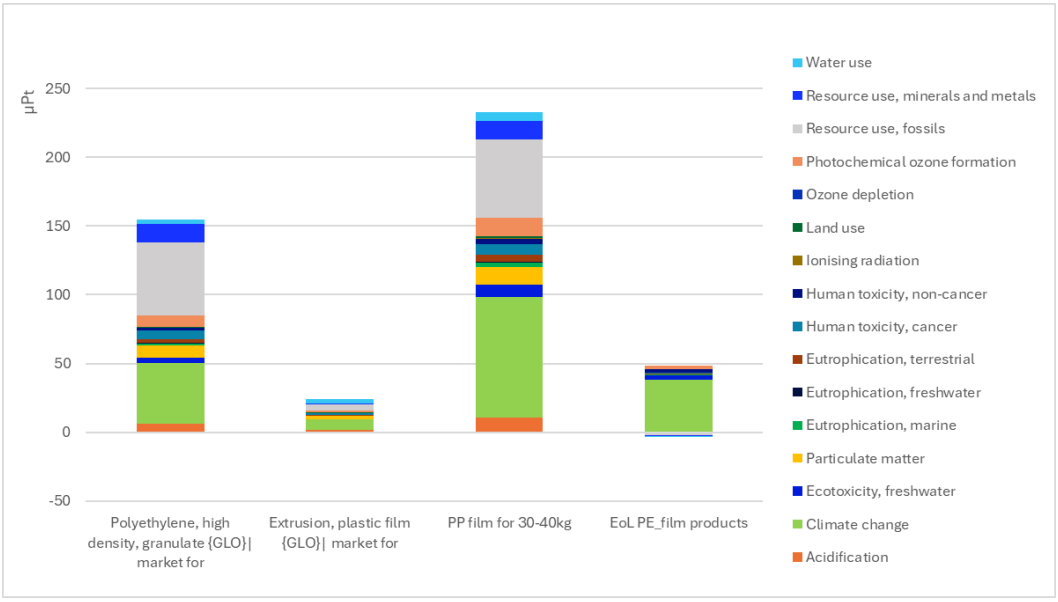


Figure 18 Bags for primary packaging LCIA, Single score results: PP and PE layers, 1 kg

e) Sanitary disposable pads with wings

Disposable pads are provided in the WASH kits to provide menstrual protection to female beneficiaries. They are made mainly from polypropylene (PP), an absorbent layer in wood pulp and a barrier liner in copolymer.

The LCIA results with EF3.1 methodology highlight 6 hotspots for this material:

Table 13 Disposable pads LCIA, impact categories hotspots and results: 1 kg

Midpoint impact categories *(EF3.1, hotspots 80%)*	Unit	Pads 1kg	Contribution (%)	Hotspots, process contribution (80%)
Particulate matter	disease incidence	9,23E-07	29,95	EoL

Midpoint impact categories *(EF3.1, hotspots 80%)*	Unit	Pads 1kg	Contribution (%)	Hotspots, process contribution (80%)
Climate Change	kg CO_2 Eq	3,40E+00	20,45	PP > Groundwood pulp > EoL
Resource Use, fossils	MJ	5,26E+01	14,52	PP > Groundwood pulp > copolymer
Human Toxicity, cancer	CTUh	2,31E-08	6,15	EoL > PP
Ecotoxicity, freshwater	CTUe	7,09E+01	5,17	EoL > PP
Photochemical ozone formation	kg NMVOC eq	1,67E-02	4,21	EoL > PP
Eutrophication, freshwater	kg P eq	7,87E-04	2,96	PP > groundwood pulp
Land Use	dimension-less (pt)	7,56E+01	1,58	Groundwood pulp
Water Use	m^3 world eq	8,22E-01	1,31	PP > groundwood pulp > copolymer

From the table above and the figures below, the most contributing processes are:

- Polypropylene textile: dataset based on 2017 data and reviewed in 2019, good representation of the technology, with low geography representativeness,
- EoL by open burning (municipal solid waste) (see section IV.B.1)
- Groundwood pulp (absorbent layer); dataset based on 2007 data and reviewed in 2020, approximation of the technology, with low geography representativeness,

Propylene textiles have the most significant impact on the use of fossil resources and Climate Change due to the use of fossil-based plastic. PP granulate production impacts are associated with propylene synthesis, the monomer for PP production.

Impacts related to municipal solid waste open burning are explained in V.B.2.c) and justified in section IV.B.1.

The production of groundwood pulp contributes to Climate Change and the use of fossil resources due to the electricity and heat required to process the wood into pulp. The growing of the wood also has impacts on land use but is it to be taken carefully as the dataset is a proxy.

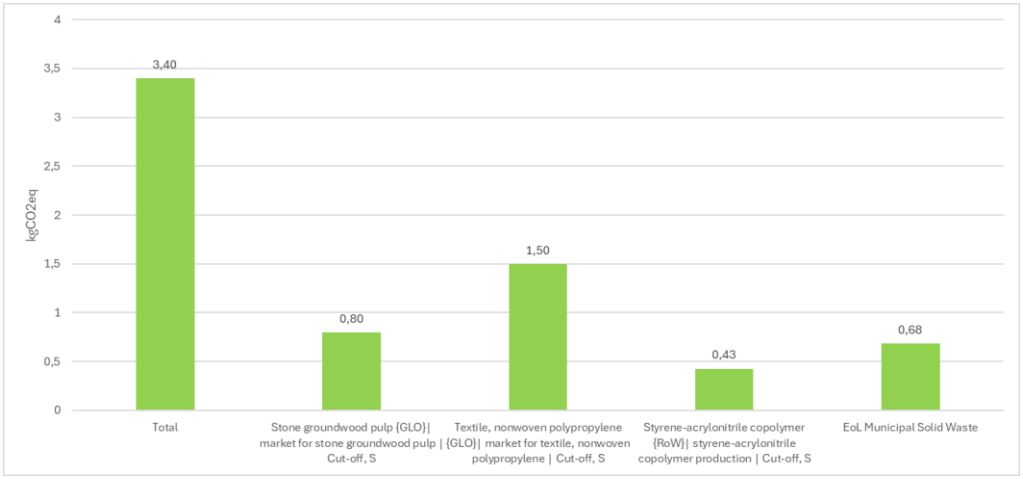


Figure 19 Disposable Pads LCIA, Climate Change results: 1 kg

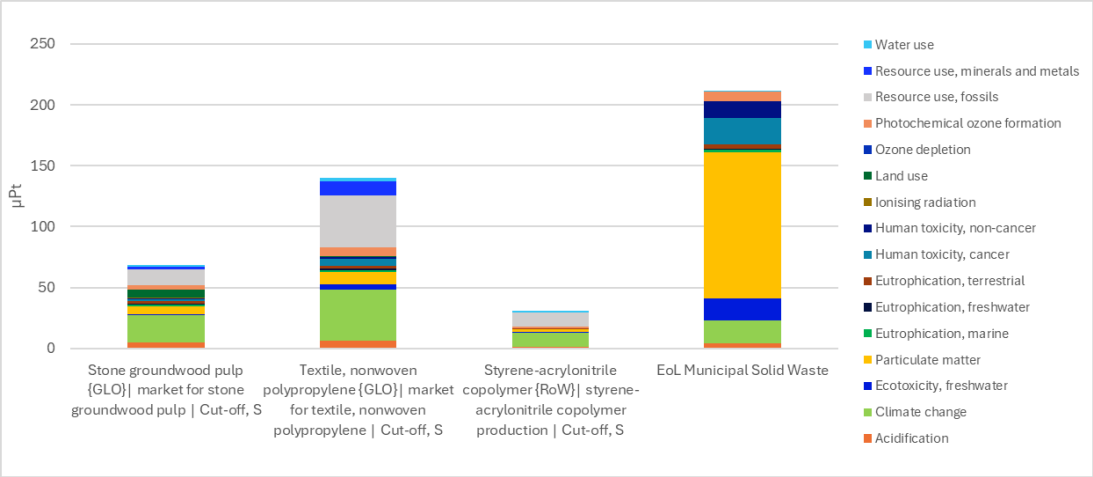


Figure 20 Disposable Pads LCIA, Single score results: 1 kg

f) Mosquito nets materials

Humanitarian organisations provide mosquito nets in the NFI kits to provide protection to the beneficiaries. Currently, mosquito nets are made of polyester fibres, coated with pesticides.

The LCIA results with EF3.1 methodology highlight seven hotspots for this material:

Table 14 Mosquito nets LCIA, impact categories hotspots and results: Polyester fibres, 1 kg

Midpoint impact categories *(EF3.1, hotspots 80%)*	Unit	For 1kg	Contribution (%)	Hotspots, process contribution (80%)
Climate Change	kg CO_2 Eq	7,80E+00	32,6	PET fibres > EoL
Resource Use, fossils	MJ	1,01E+02	19,44	PET fibres
Resource Use, minerals and metals	kg Sb eq	4,39E-05	7,81	PET fibres > Weaving
Photochemical ozone formation	kg NMVOC eq	3,81E-02	6,69	PET fibres > EoL
Human Toxicity, cancer	CTUh	3,54E-08	6,55	PET fibres > EoL
Particulate matter	disease incidence	2,71E-07	6,11	PET fibres
Acidification	mol H^+ eq	3,10E-02	5,18	PET fibres > EoL
Ecotoxicity, freshwater	CTUe	5,67E+01	2,88	PET fibres > EoL
Water Use	m^3 world eq	1,29E+00	1,44	PET fibres
Eutrophication, freshwater	kg P eq	3,09E-04	0,81	PET fibres
Land Use	dimensionless (pt)	1,58E+01	0,23	PET fibres

From the table above and the graphs presented in Figure 21 and Figure 22, the most impactful processes are:

- Polyester fibres (generally PET, fossil-based) production; dataset based on 2018 data and reviewed in 2021, good representation of the technology, with low geography representativeness
- And EoL by open burning (of a plastic mixture) (see section IV.B.1)

Polyester fibre production single score analysis displays impacts due to the use of PET (saturated thermoplastic polyester) as the primary material. As presented in V.B.2.c), PET is responsible for high impacts associated with terephthalic acid and ethylene synthesis, monomers for PET production: Resource Use, fossils, Climate Change, Resource Use, minerals and metals, Particulate matter, and Photochemical ozone formation.

Unlike other plastic transformation processes, weaving does not significantly contribute to the mosquito net material impacts. Indeed, the transformation process from PET granulate to polyester fibres is already included in polyester fibres production. Moreover, the energy requirements for weaving are relatively low.

To conclude, mosquito nets made of polyester fibres coated with pesticides have their main impact coming from raw materials. EoL also has important impacts, contributing to around 20% to total single score results. It is also interesting to note that pesticides have no crucial impacts on any of these categories, mostly due to the low quantity needed.

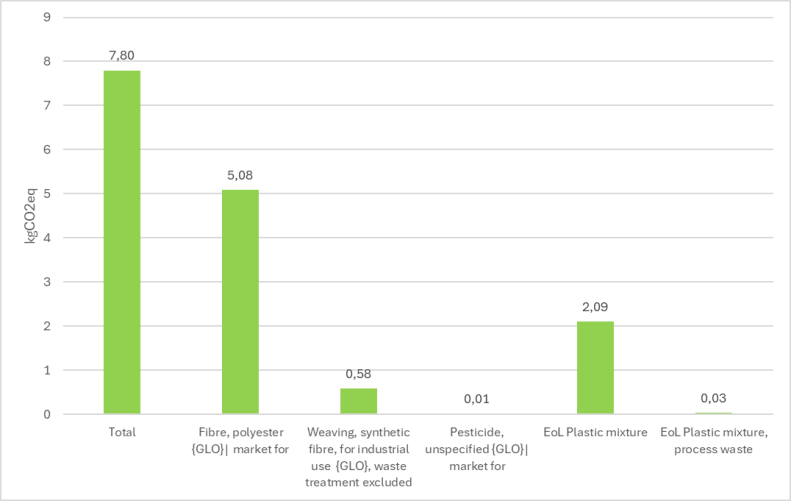


Figure 21 Mosquito net LCIA, Climate Change results: Polyester fibres, 1 kg

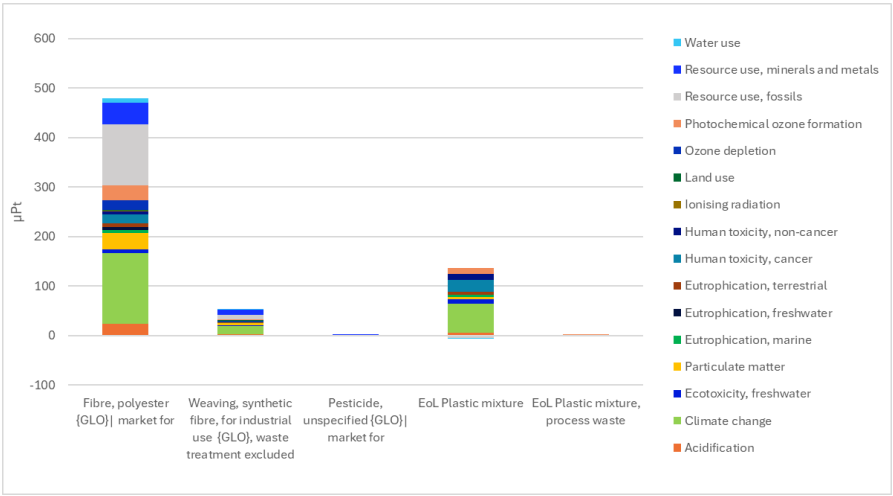


Figure 22 Mosquito net LCIA, Single score results: Polyester fibres, 1 kg

g) PE laminating film for tertiary packaging

The kits are assembled, stored at humanitarian storage centres and then sent to the field. To do so, the kits are placed onto a pallet and wrapped with PE film to ensure the pallet's structural integrity during transportation.

The LCIA results with EF3.1 methodology highlight five hotspots:

Table 15 PE laminating film for tertiary packaging LCIA, impact categories hotspots and results: 1kg

Midpoint impact categories *(EF3.1, hotspots 80%)*	Unit	For 1kg	Contribution (%)	Hotspots, process contribution (80%)
Climate Change	kg CO_2 Eq	7,13E+00	40,75	LDPE > EoL
Resource Use, fossils	MJ	9,40E+01	24,66	LDPE
Photochemical ozone formation	kg NMVOC eq	2,45E-02	5,88	LDPE > EoL
Resource Use, minerals and metals	kg Sb eq	2,39E-05	5,81	LDPE
Particulate matter	disease incidence	1,63E-07	5,02	LDPE
Ecotoxicity, freshwater	CTUe	4,85E+01	3,36	LDPE > EoL
Water Use	m_3 world eq	1,17E+00	1,78	LDPE
Eutrophication, freshwater	kg P eq	1,27E-04	0,45	LDPE > Extrusion
Land Use	dimensionless (pt)	1,05E+01	0,21	LDPE

From the graphs presented in Figure 23 and Figure 24, the most impactful processes are:

- Low-Density Polyethylene (LDPE) production; dataset based on 2016 data and reviewed in 2021, accurately represent the technology, with low geography representativeness
- And, EoL by open burning of the multimaterial (municipal solid waste) (see section IV.B.1)

As mentioned in the previous sections, PE production has impacts on Resource Use, fossils, Climate Change, Resource Use, minerals and metals, Particulate matter, and Photochemical ozone formation due to ethylene monomer production.

To conclude, PE film as tertiary packaging presents impacts coming from the synthesis of raw materials, namely PE. EoL has non-negligible impacts on Climate Change and contributes to freshwater Ecotoxicity.

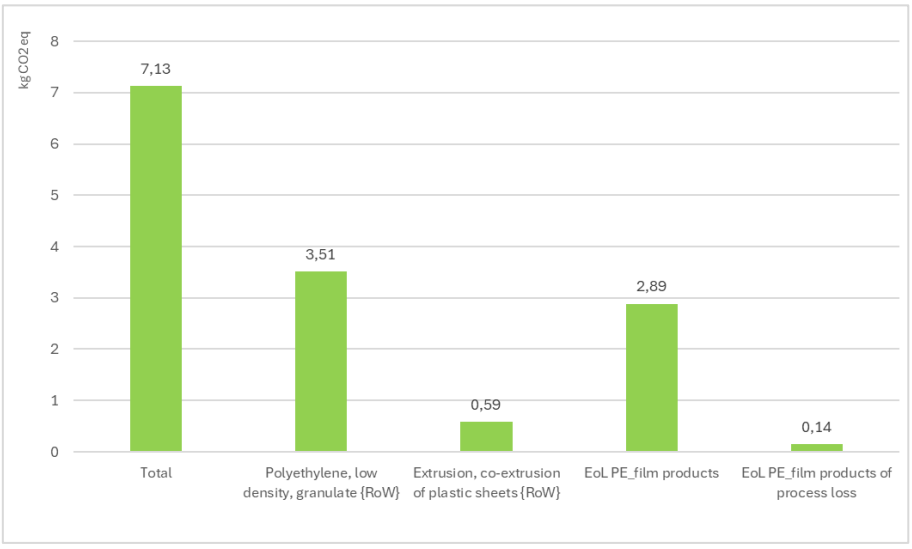


Figure 23 PE laminating film for tertiary packaging LCIA, Climate Change results: 1 kg

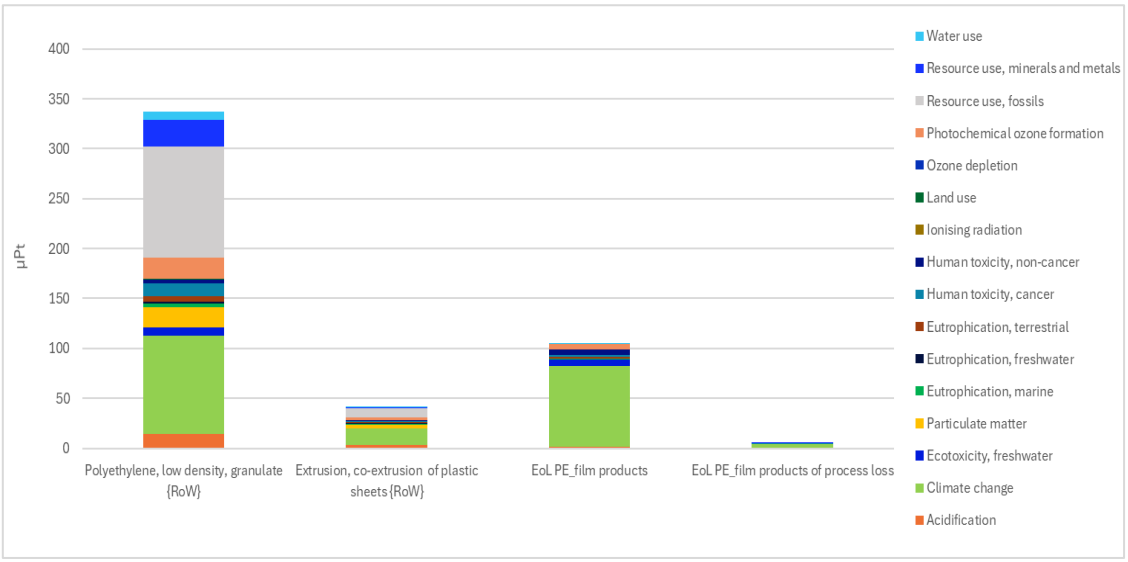


Figure 24 PE laminating film for tertiary packaging LCIA, Single score results: 1 kg

h) Adhesive tape

Adhesive tape is used to secure the cardboard and polypropylene bags in secondary or tertiary packaging in all kits. It is made with PVC film, plasticisers (modelled as organic chemicals), synthetic rubber, binder, and calcium carbonate.

The LCIA results with EF3.1 methodology highlight seven hotspots for this material:

Table 16 Adhesive tape LCIA, impact categories hotspots and results: 1 kg

Midpoint impact categories *(EF3.1, hotspots 80%)*	Unit	Value for 1kg	Contribution (%)	Process contribution (80%)
Particulate matter	disease incidence	9,45E-07	26,53	EoL
Climate Change	kg CO_2 Eq	3,92E+00	20,36	PVC > Plasticizers > EoL

Midpoint impact categories *(EF3.1, hotspots 80%)*	Unit	Value for 1kg	Contribution (%)	Process contribution (80%)
Resource Use, fossils	MJ	6,53E+01	15,59	PVC > Plasticizers > Rubber
Human Toxicity, cancer	CTUh	3,62E-08	8,34	EoL > Plasticizers > PVC
Resource Use, minerals and metals	kg Sb eq	2,84E-05	6,29	PVC > Plasticizers > Rubber
Ecotoxicity, freshwater	CTUe	7,93E+01	5,00	EoL > PVC
Water Use	m^3 world eq	1,62E+00	2,25	PVC > Extrusion > Plasticizer > rubber
Eutrophication, freshwater	kg P eq	1,51E-04	0,49	PVC > Plasticizers > Extrusion
Land Use	dimensionless (pt)	1,37E+01	0,25	PVC > Extrusion > Plasticizers

From the table above and the figures below, the most contributing processes are:

- PVC: dataset based on 2007 data and reviewed in 2011, accurately represent the technology, with low geography representativeness
- EoL (municipal solid waste) (see section IV.B.1)
- Plasticisers (organic chemicals): dataset based on 2011 data and reviewed in 2014, proxy for phthalates plasticisers, with low geography representativeness

Polyvinyl Chloride is a fossil-based plastic made from ethylene through an energy intensive process, generating impacts in Climate Change, use of fossil and mineral resources. The dataset has not been reviewed recently and even if it correctly represents the technology, the data quality can be considered only as average.

The plasticisers in PVC tape are typically phthalate-based. Since no specific datasets for phthalate plasticizers are available in ecoinvent 3.10, they were approximated using the *market for organic chemicals* dataset. This proxy results in the highest contributions to Climate Change and fossil Resource Use but may underestimate impacts in categories such as Human Toxicity and Ecotoxicity, where phthalates are known to be more relevant.

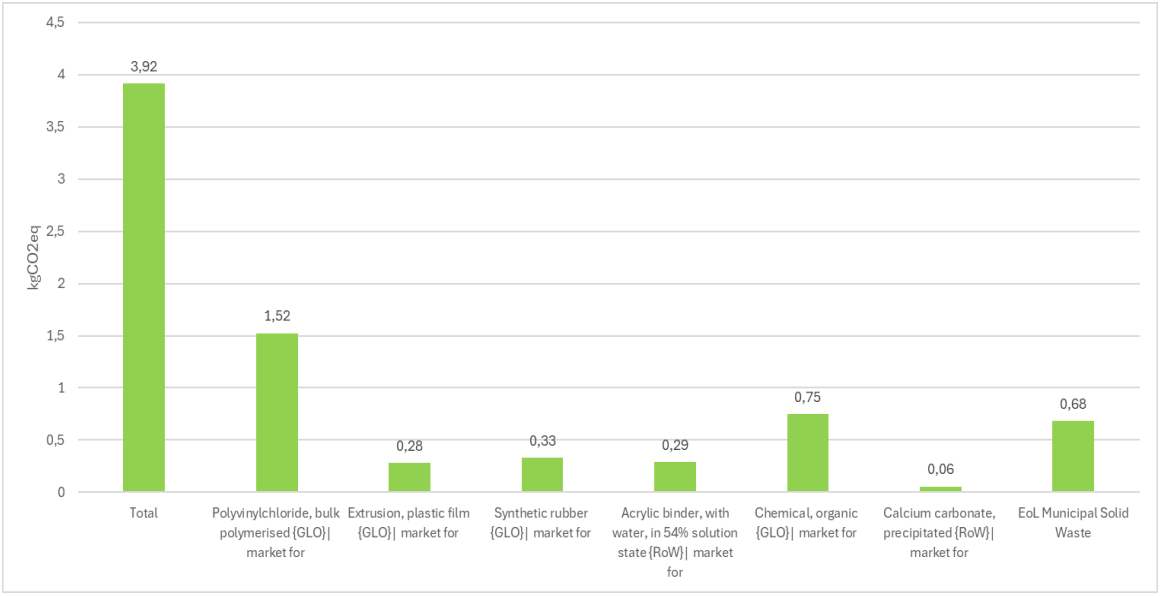


Figure 25 Adhesive tape LCIA, Climate Change results: 1 kg

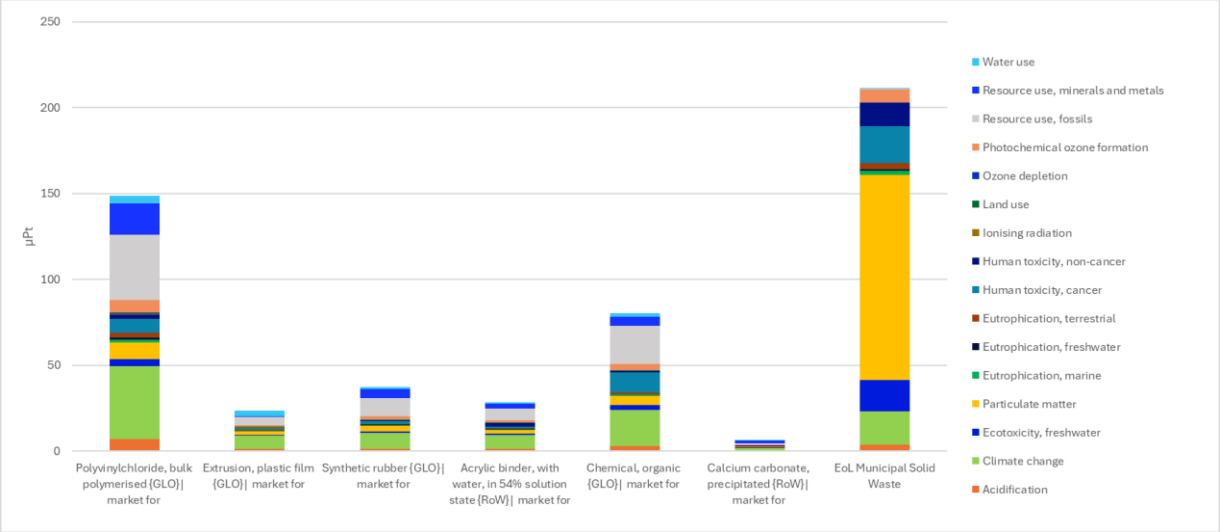


Figure 26 Adhesive tape LCIA, single score results: 1 kg

i) Building insulation materials

Although thermal insulation materials may not be a short-term solution in countries such as the DRC or SS, they were nevertheless included in the analysis to assess their potential replicability in other humanitarian contexts where building insulation is relevant, i.e. cold weather (e.g., Ukraine). The reference material is a glass wool material. For EoL, open burning of glass was selected to ensure coherence across the study, as data on open dumping in ecoinvent lacks consistency and could not be applied uniformly.

The present study adopts a functional unit of 1 kg to remain consistent with the rest of the materials analysed in this report, regardless of the material's thermal insulation properties. This choice ensures methodological coherence in this deliverable where solutions are not to be compared between one another. In

deliverable D5.3, insulation materials will be compared based on 1 m² of insulation to better capture their actual functionality.

The LCIA results with EF3.1 methodology highlight six hotspots for this material:

Table 17 Glass wool insulation LCIA, impact categories hotspots and results: 1 kg

Midpoint impact categories *(EF3.1, hotspots 80%)*	Unit	Values for 1kg	Contribution (%)	Hotspots, process contribution (80%)
Climate Change	kg CO_2 Eq	3,25E+00	26,99	Glass wool
Resource Use, fossils	MJ	4,27E+01	16,30	Glass wool
Resource Use, minerals and metals	kg Sb eq	4,55E-05	16,11	Glass wool
Human Toxicity, cancer	CTUh	2,20E-08	8,09	Glasswool > EoL
Particulate matter	disease incidence	1,75E-07	7,87	Glass wool
Acidification	mol H^+ eq	1,99E-02	6,63	Glass wool
Water Use	m^3 world eq	1,14E+00	2,51	Glass wool
Ecotoxicity, freshwater	CTUe	2,31E+01	2,34	Glass wool
Eutrophication, freshwater	kg P eq	1,27E-04	0,66	Glass wool
Land Use	dimensionless (pt)	8,94E+00	0,26	Glass wool

The production of glass wool has more significant impacts than open burning at the EoL. The impact comes mainly from the energy-intensive melting of raw materials, silica sand among others, the formaldehyde binder production, and the direct emissions from the process.

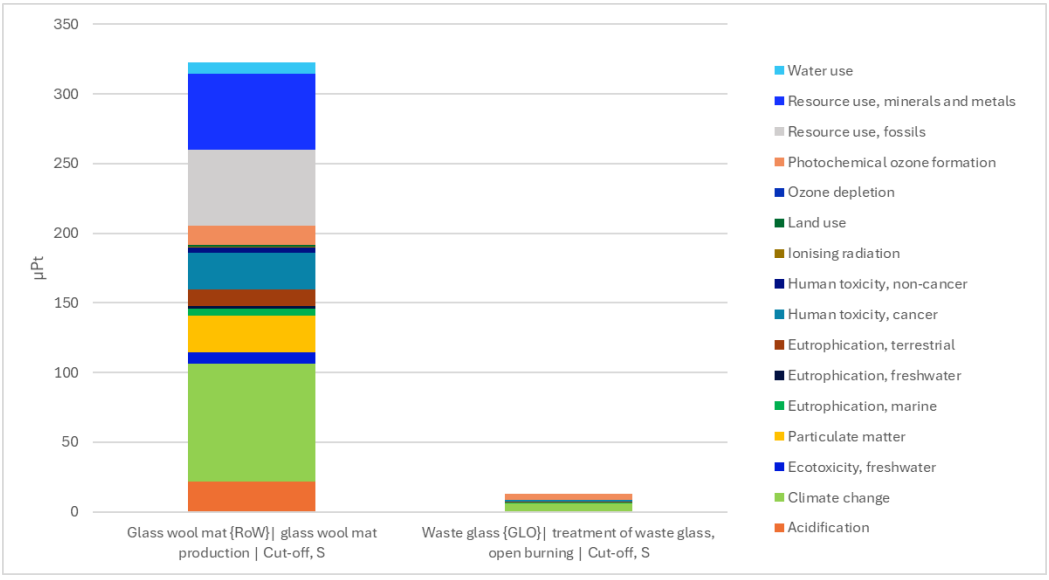


Figure 27 Glass wool insulation LCIA, single score results: 1 kg

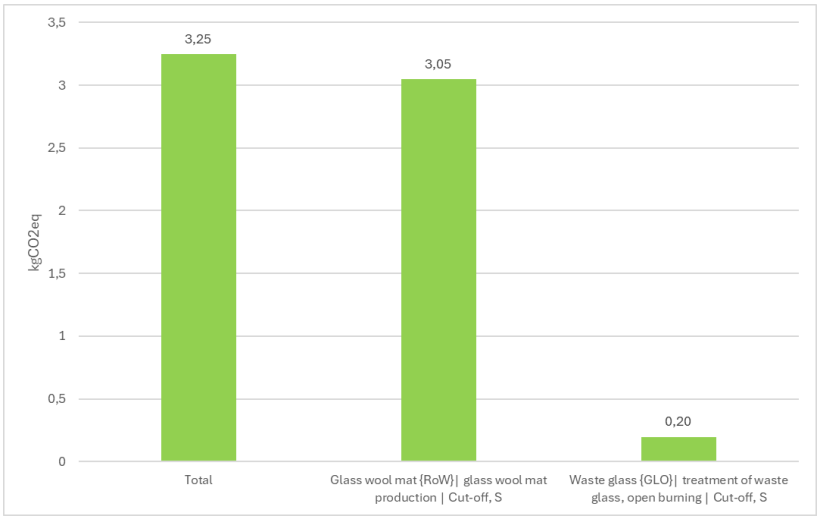


Figure 28 Glass wool insulation LCIA, Climate Change results: 1 kg

j) Fragile item Packaging

Although the kits developed within the scope of the project do not contain fragile items, the use of polystyrene protection within cardboard packaging was analysed. This aspect, while not strictly within the project scope, was described in deliverable D5.1, as it presents an interesting solution that could be relevant for future applications (e.g., medical items). The EoL treatment for polystyrene is open burning.

From the figures below, production of polystyrene (fossil-based) has equivalent impacts to that of its open burning in Climate Change, but higher impacts with a single score, especially regarding the use of fossil resources. The inventory is taken from ecoinvent 3.10 database (Polystyrene, expandable {GLO}| market for).

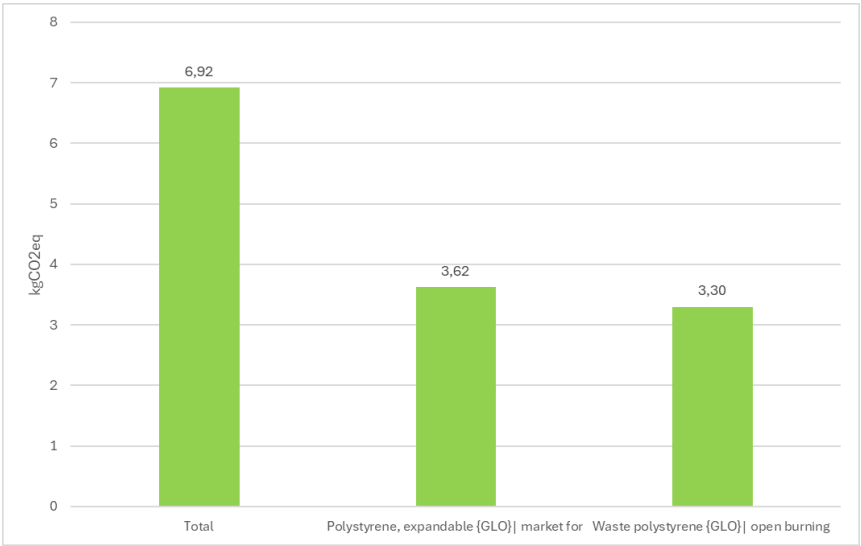


Figure 29 Polystyrene packaging LCIA, Climate Change results: 1 kg

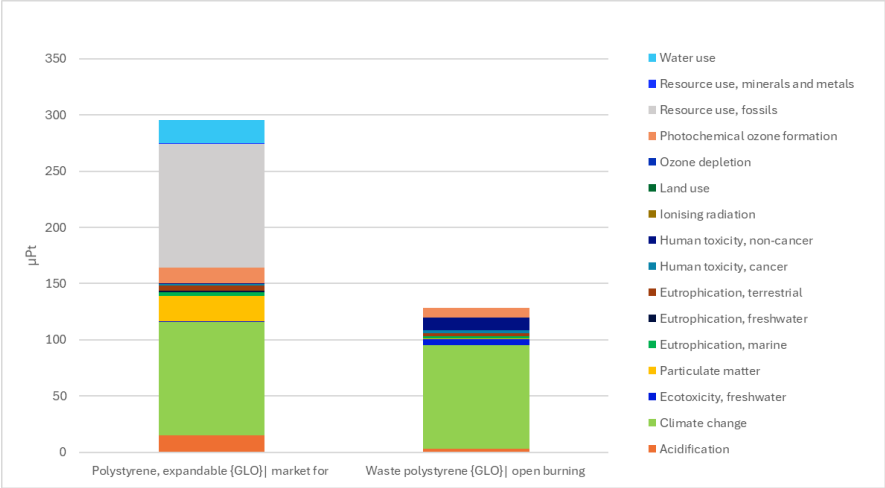


Figure 30 Polystyrene packaging LCIA, single score results: 1 kg

k) Other indicators: reference materials

To complete the hotspots analysis study, other indicators were studied: Plastic physical effect on biota (Impact World + methodology), Biogenic C uptake and emissions -1/+1 (EN15804+A2), and MDI Material Durability Indicator.

Criticality of PLA and PE will also be assessed qualitatively but in another chapter: VI.A.

(1) Plastic physical effect on biota

This indicator is calculated with the IW+ 2.1 methodology and is implemented in SimaPro. It translates plastic effects on ecosystems based on an article which explains the methodology and categories of microplastics[34]. Microplastics were associated with open dumping and unsanitary landfill of fossil plastics of the reference scenario (see IV.B.1). Considering this indicator allows for consistency with the D5.1 EoL reference scenario, which assumes 10% collection, 10% open burning, and 80% open dumping. While the EoL impacts of reference items would appear lower when open dumping is included instead of open burning (see section IV.B.1), this indicator captures the negative consequences of open dumping. It is therefore recommended to use the “plastic effect on biota” indicator as complementary whenever open dumping is considered.

Table 18 presents how harmful each material could be to the environment. To read this table, it must be considered that 10% of total material mass is open burnt (data from D5.1) and not concerned by plastic scattering, and hence, is not involved in plastic's physical effect on biota.

[34] MarILCA characterization factors for microplastic impacts in life cycle assessment: Physical effects on biota from emissions to aquatic environments

Table 18 Plastic physical effect on biota of concerned products material from IW+ (1kg)

Product material (1kg)	Oil HDPE jerrycan	LDPE water container	Pouch for RUTF	Adhesive tape	PE film	PE/PP bag	Disposable pads	Mosquito net
Reference material wt%	HDPE 100	LDPE 100	PET 41,2 LDPE 48,6	PVC 45	HDPE 100	HDPE 51 PP 49	HDPE - 9 PP - 3 PS - 1	PET 86,2
Plastic microplastic shape (default size)	Film fragments						Film / Micro-fibers / Film	Micro-fibers
Plastic effect on biota	**413,9**	**256,3**	**146,5**	**5,8**	**414,3**	**244,1**	**581**	**0,8**
Unit	**PDF.m^2.yr**							

PE impacts are due to its medium/low density so the plastics will spread by floating into the ocean, and then slowly fragment into films. Films tend to persist longer times on surfaces and smother them.

PVC from tape impacts can be explained by its high density that draws PVC fragments to be trapped in freshwater sediments. Hence, PVC is associated to low residence time in water and exhibits limited impact.

PET fibres are endangering biodiversity due to their high ingestion likelihood, but it is mitigated by its high density (short residence time).

(2) Biogenic carbon uptake

The materials studied for the reference scenario are fossil-based. No carbon content can be associated with biogenic carbon. The indicator does not provide added value in the reference scenario, but it helps highlight the absence of biogenic carbon capture in fossil-based solutions, a feature that is addressed by the solutions analysed in the project.

(3) Ecosystem quality

This indicator reflects the impact of a process on biodiversity (PDF.m^2.yr). It aggregates environmental impacts into damages (endpoint, see VIII.C) Figure 31 displays how each material of this section affects biodiversity during its entire life cycle. 1kg of RUTF pouch, disposable pads, and adhesive tape have the most impact on the quality of ecosystems. However, these materials have different functionalities and the impacts on ecosystem results are not intended to be compared between one another.

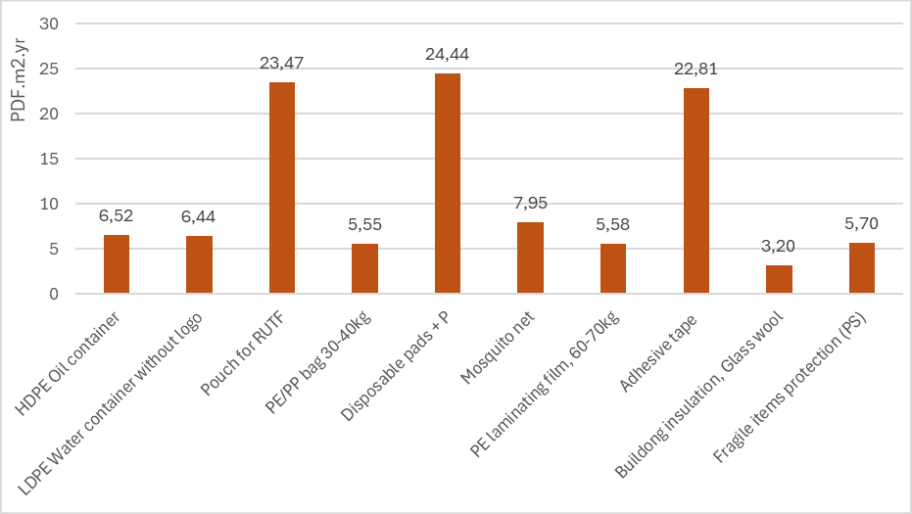


Figure 31 Reference materials impact on Ecosystem quality: Impact World+ v2.1: 1kg

(4) Material Durability Indicator (MDI)

The MDI is intended to capture the durability aspect of materials, covering mechanical and chemical durability as well as their environmental impact.

With the eight indicators mentioned in III.B.3 retrieved from literature, an MDI of the reference material was calculated. Results are available in Table 19.

Table 19 Material Durability indicator of reference materials, building insulation excluded

Product material (1kg)	Oil jerrycan	Water container	Pouch for RUTF	Adhesive tape	PE film	PE/PP bag	Disposable pads	Mosquito net	Fragile items packaging
Base material CONSIDERED	HDPE	LDPE	PE (medium density)						PS
MDI	29,3	22,2	12,9	27,9	23,5	33,0	28,2	21,8	33,0
Unit	No unit, between [1;400]								
References *(MR= mechanical resistance; ChR= chemical resistance*	MR; Fatigue at 1e7 ; UV resistance; ChR	MR; Fatigue at 1e7 ; ChR	MR; ChR						MR; UV resistance; ChR

PE-based materials have a relatively low MDI because of important energy consumption and low flammability resistance, and their mechanical properties (i.e., yield strength and resistance to fatigue) are rather low.

Expanded PS packaging for fragile items has a low MDI due to its low flammability resistance and low mechanical properties.

Based on this assessment methodology, none of the studied materials have interesting durability properties.

3. Solutions

a) PLA production impact assessment and analysis

As a base solution material, polylactic acid (PLA) was detected as an available bio-based and compostable solution. PLA is based on the polymerisation of lactic acid, synthesized from glucose.

PLA is compostable under specific conditions. If the product has the compostability certification, then it degrades with no toxicity for the environment under controlled conditions. In this sense, if the product complies with the UNE 13432 that sets requirement for packaging industrial composting and biodegradation, ensuring the following:

- Biodegradability
- Harmless disintegration products
- No toxicity
- Compost quality.

To obtain glucose, starch of bioproducts (crops or biowaste) is chemically hydrolysed. The yield of lactic acid production from a defined mass of bioproducts depends on the lignocellulosic content and water content of the base material. Biowaste resources correspond to agricultural or food waste, so the composition of the collected biowaste can vary, as well as the yield for PLA production.

To define the impacts of PLA production, a literature review was conducted to extract process inventories for PLA production. Therefore, four different processes were modelled based on four different source materials (bioproducts) and two different recycling methods. The inventories are available in the Annex VIII.B.1.

Table 20 PLA production: literature for different production processes

Base bioproduct	Source	Year	Data quality
Maize	From ecoinvent 3.10: Polylactic acid from biowaste, granulate {GLO}| polylactic acid production, granulate | Cut-off, U	2007, reviewed in 2012	Complete, current, Global geography (based on Nebraska plant)
Sugarcane	Dataset made from "Techno-economic and environmental assessment of polylactic acid production integrated with the sugarcane value chain"[35]	2022	Complete, current, Brazil adapted to Global geography
Biowastes	ecoinvent 3.10 PLA from maize dataset adapted from "life cycle analysis of polylactic acids from different wet waste feedstocks"[36]	2023	Adapted proxy (yield scaling factor, current, Global geography
Fruit biowastes	Sugarcane PLA dataset adapted with "Life Cycle Impact Assessment of Polylactic Acid (PLA) Produced from Sugarcane in Thailand"[37]	2019	Adapted proxy, current, Brazil adapted to Global geography

[35] Bressanin et al. (2022) https://doi.org/10.1016/j.spc.2022.09.009
[36] Angelin Swetha et al. (2023) https://doi.org/10.1016/j.ijbiomac.2023.123703
[37] Morão & De Bie (2019) https://link.springer.com/article/10.1007/s10924-019-01525-9#Bib1

Base bioproduct	Source	Year	Data quality
Mechanical recycling	From ecoinvent 3.10: PLA from maize dataset adapted from "Life cycle assessment of recycling options for polylactic acid"[38]	2019	Proxy, current, Global geography
Chemical recycling	ecoinvent 3.10 PLA from maize dataset adapted from "Valorisation of polylactic acid (PLA) waste: A comparative life cycle assessment of various solvent-based chemical recycling technologies"[39]	2021	Proxy, current, Europe adapted to Global geography

Based on this review, a diagram synthesising virgin PLA production has been developed in Figure 32.

Environmental impacts can vary based on the source material, as the process involves several variables:

- Pre-treatment of base material depends on its water content and lignocellulosic content. Therefore, the yield ratio between the source material and the lactic acid can vary.
- Chemical hydrolysis can be avoided if free sugars are available (e.g. with sugarcane as base material).
- Co-products can be obtained during pre-treatment, for instance (e.g. with sugarcane as base material).
- Polymerisation is most often done through polycondensation or ring-opening polymerisation (ROP).

Table 21 presents the process steps and assumptions used to develop the inventories of PLA production, based on the literature. These inventories represent generic processes but do not represent actual environmental impacts because numerous hypotheses were elaborated, especially in the case of PLA based on biowaste. It gives, however, a general idea of the possible impacts and impact differences between PLA granulates based on different raw materials.

Regarding PLA produced from recycled PLA, the inventories were retrieved from Bio4HUMAN deliverable D5.1.

[38] Maga et al. (2019) https://doi.org/10.1016/j.resconrec.2019.05.018
[39] Aryan et al. (2021) https://doi.org/10.1016/j.resconrec.2021.105670

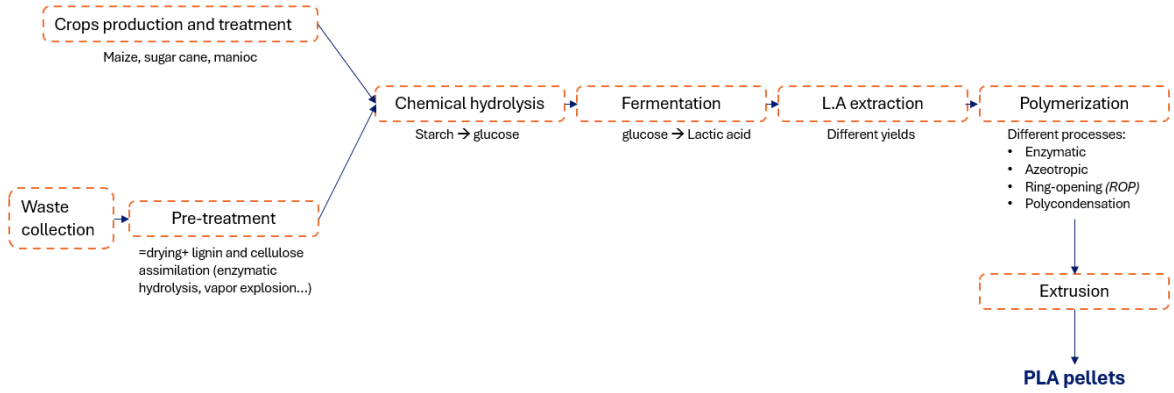


Figure 32 PLA synthesis diagram, from crops or from biowaste

Table 21 Different PLA production processes. Sources mentioned in Table 20. Struck-off steps are not included in the modelling and represent differences between the production pathways.

PLA production from	Process representative diagram
Maize	Crops production and treatment (Maize) → Chemical hydrolysis (Starch → glucose) → Fermentation (glucose → Lactic acid) → L.A extraction (Different yields) → Polymerization (• Ring-opening (ROP)) → Extrusion → PLA pellets
Sugarcane*	Crops production and treatment (Sugar cane) → ~~Chemical hydrolysis~~ (Free sugars available) → Fermentation (glucose → Lactic acid) → L.A extraction (Different yields) → Polymerization (Different processes: • Ring-opening (ROP) • Polycondensation) → Extrusion → PLA pellets Economic allocation: +Molasses for ethanol production, +Electricity, +Filter cake (N, P), +Gypsum → Ethanol
Biowastes	~~Waste collection~~ (Biowaste, average world) → Pre-treatment (=drying+ lignin and cellulose assimilation (**enzymatic** hydrolysis, vapor explosion...)) → Chemical hydrolysis (Starch → glucose) → Fermentation (glucose → Lactic acid) → L.A extraction (Different yields : sensitivity analysis) → Polymerization (• Ring-opening (ROP)) → Extrusion → PLA pellets
Fruit Biowastes*	~~Waste collection~~ (Biowaste, average world) → Pre-treatment (=drying) → ~~Chemical hydrolysis~~ (Free sugars available) → Fermentation (glucose → Lactic acid) → L.A extraction (Different yields) → Polymerization (Different processes: • Polycondensation • Ring-opening (ROP)) → Extrusion → PLA pellets Economic allocation: +Molasses for ethanol production, ~~+Electricity~~, +Filter cake (gypsum,N, P) → Ethanol No bagasse burning → no credit + need of energy for pre-treatment

*Economic allocation associates 57,6% of the impacts to the 22kg of produced PLA (from 1 t of processed waste) (Bressanin et al., 2022)). 34.9% is associated to ethanol, 0.6% to gypsum, and 6.9% to electricity (when produced)

In Figure 33, a display of all the different PLA environmental impacts with EF3.1 impact categories is available. This graph shows that each PLA has different impacts and hotspots. Virgin PLAs display higher global impacts than recycled ones. Figure 34 gives an overview of the mandatory impact categories that are to be studied for Bio4HUMAN, and additional identified hotspots of the various PLAs.

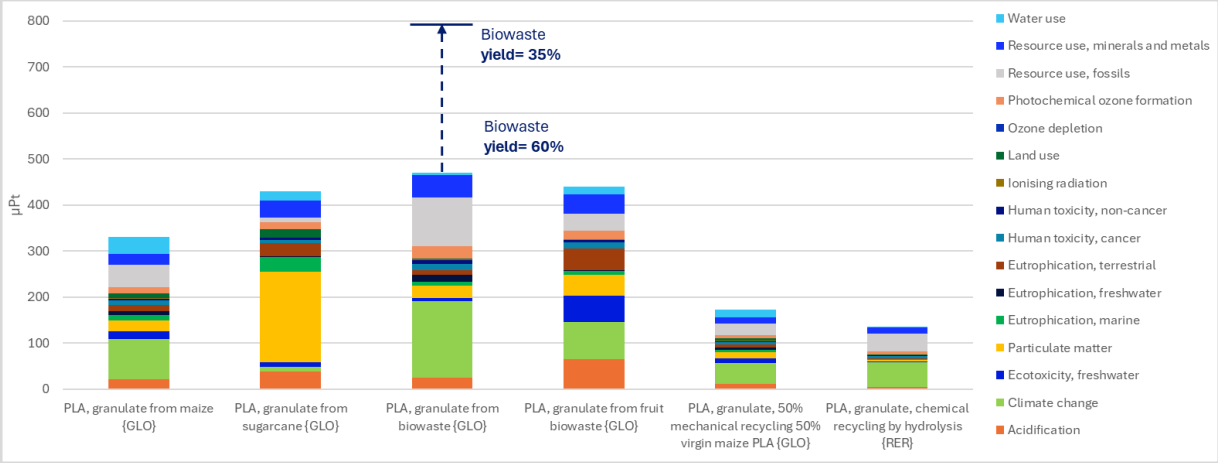


Figure 33 Environmental impacts (EF3.1) of PLA production processes (1kg), cradle-to-gate, Single score

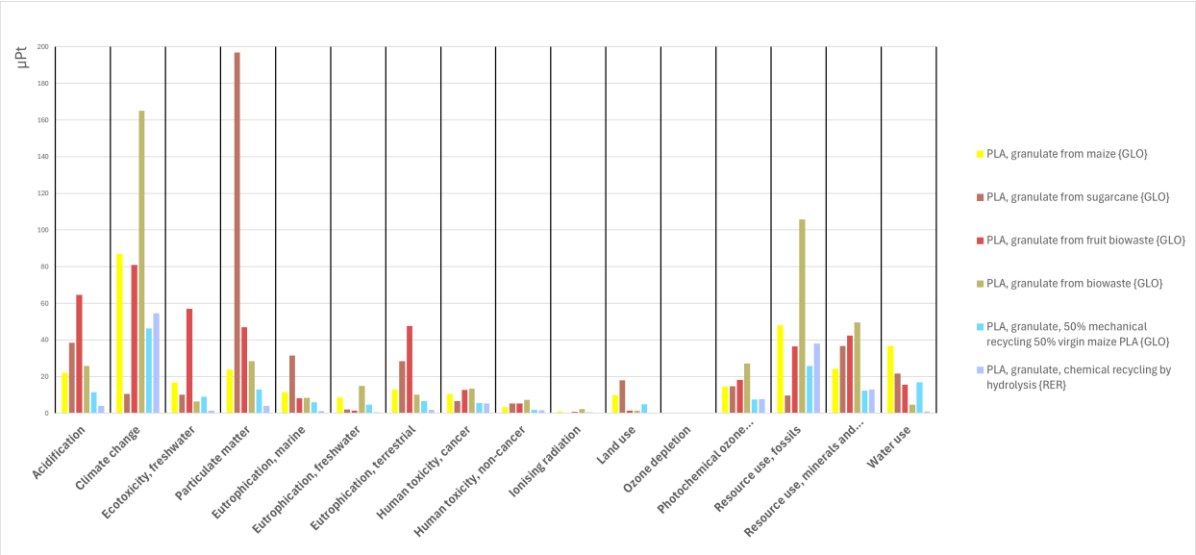


Figure 34 Environmental impacts (EF3.1) of PLA production processes (1kg), cradle-to-gate, impact category per impact category

From these results, it can be deduced that biowaste-based PLA does not offer better environmental performance based on EF3.1 methodology and assumptions made in Table 21 and detailed in the following paragraphs, as well as in the inventories of Annex VIII.B.1. Although the environmental impacts of PLA derived from biowaste are higher compared to other options, it is still considered a correct solution within the project context to avoid Water Use and Land Use due to sugarcane and maize agriculture. Also, the use of waste streams avoids competition with food production and supports circular resource use. However, process improvements, particularly through biowaste local valorisation and the integration of renewable energy, are necessary to enhance the environmental performance and make this solution more competitive. For instance, lower impact would be expected if the process happens in DRC rather than in SS as most of the energy used in DRC is hydraulic compared to the oil-based energy in SS, as developed in section VI.A.

On one hand, biowaste that undergoes the same treatment process as maize is associated with a significantly lower process yield: the global biowaste humidity content presented is at 58%, compared to about 35% for maize. Furthermore, maize presents a yield (dry mass/PLA mass) of almost 100%, whereas biowaste yields found in the literature range from 35% (manure) to 60% (cotton and coffee), approximately. Therefore, energy consumption and other inputs were multiplied by scaling factors of 2.6 and 4.4, respectively. Equation 4 presents how these factors were calculated, based on waste humidity content and yield.

Equation 4 Scaling factor calculation for PLA production based on biowaste

$$scaling\ factor = \frac{waste\ input\ (wet)}{maize\ input\ (wet)} = \frac{\frac{1}{(1-humidity\ content)}.waste\ input\ (dry)}{maize\ input\ (wet)} = \frac{\frac{1}{(1-humidity\ content)}.\frac{PLA\ output}{yield}}{maize\ input\ (wet)}$$

So, despite cancelling the impacts of maize production (Water Use, Ecotoxicity, freshwater), biowaste-based PLA generates higher impacts in terms of Climate Change, Resource Use, Eutrophication, freshwater, Human Toxicity, and Photochemical ozone formation. Figure 35 shows that these impacts are related to electricity and heat from natural gas consumption. Here, the generic dataset used for energy is global representative. With more specific data, adapted to the region of production and taking into account regional environmental challenges, it may be beneficial to use biowastes as input instead of maize.

On the other hand, fruit biowaste that undergoes the same treatment process than sugarcane provides a similar yield *(around 25%, with ethanol co-production)* as sugarcane. Indeed, both products dispose of a significant content of free sugars, thus avoiding chemical hydrolysis. The necessary quantity of free sugars limits this hypothesis to fruit-based waste. However, in the case of fruit biowaste, there is no burning of sugarcane bagasse and agricultural wastes, therefore no local electricity production. Furthermore, the process waste is not necessarily valorised in the field directly, so they are considered as industrially composted waste.

Both of these modifications in the process have significant impacts on the PLA production from fruit biowaste compared to sugarcane-based: Acidification, Climate Change, Ecotoxicity, freshwater, Eutrophication, terrestrial, Human toxicity, Photochemical ozone formation, Resource Use. Figure 36 shows that these impacts indeed come from industrial composting and energy use. Note that the energy consumption related to this process was set at the same amount as for the maize process, which was used as proxy. However, actual values can vary, as the process is different. Indeed, no data was found in the literature on the actual energy consumption of the production process from sugarcane, as it is typically linked to local energy generation. The articles reviewed report only the surplus electricity sold, not the actual energy consumption of the process. Energy data adapted to the region of production may show benefits of using fruit biowastes as input instead of sugarcane (amount of electricity needs to be confirmed). Additionally, if the process waste is not put in an industrial compost but rather in local agricultural fields or home composts, the impacts will be significantly lower. Climate Change, total (EF 3.1) impacts related to PLA production from sugarcane are relatively low compared

to other PLA. This is because the electricity used for this PLA production comes from bagasse burning (374.5 kg/tonne of processed sugarcane), thus, CO_2 emissions for this electricity production are biogenic, therefore not accounted for by the EF3.1 methodology (CO_2 biogenic emission factor is equal to zero). In addition, sugarcane production enriches soil, which lowers Climate Change total results.

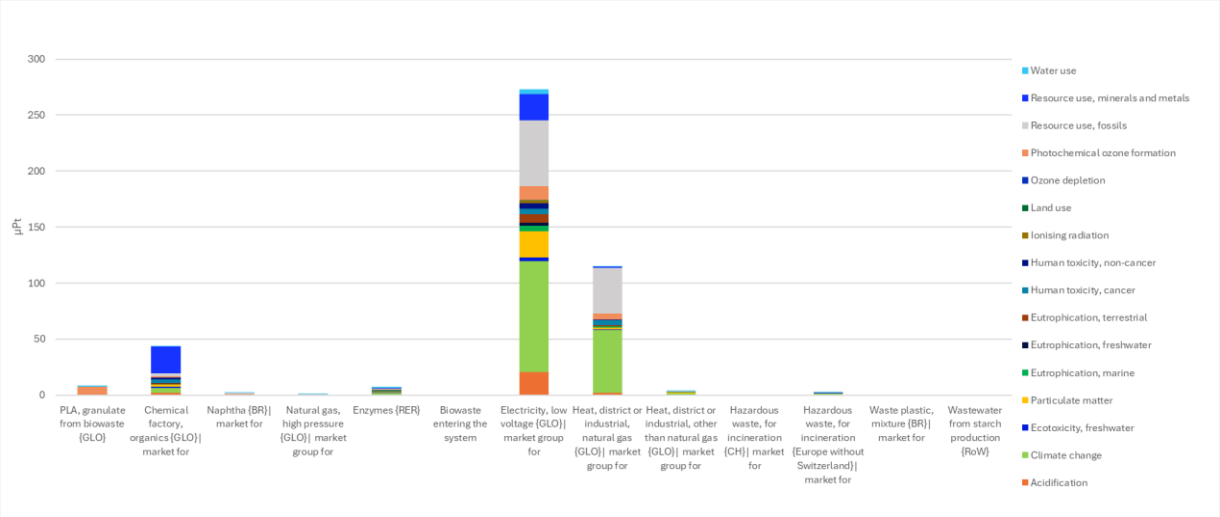


Figure 35 PLA from biowaste (dry mass/PLA yield of 60%) environmental impacts (EF3.1), Single score

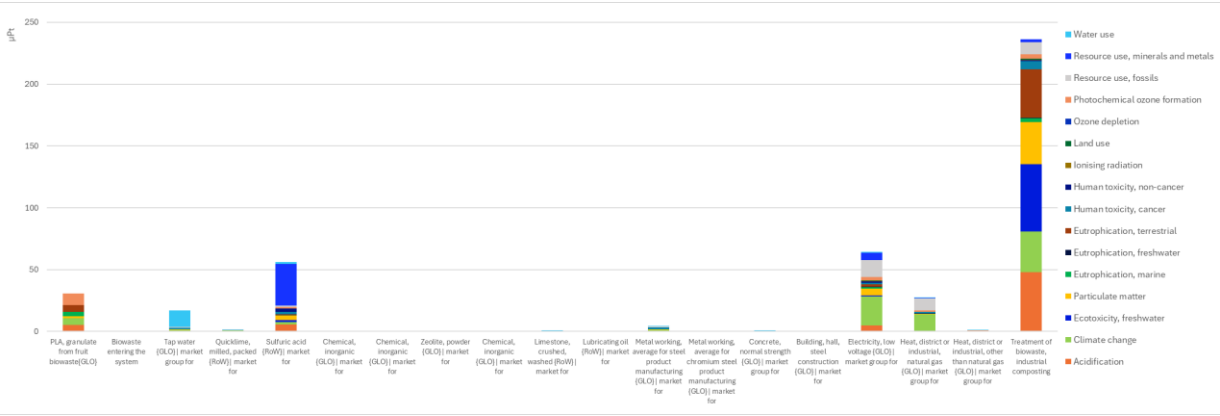


Figure 36 PLA from fruit biowaste environmental impacts (EF3.1), 61% economic allocation (co-products: ethanol and gypsum), Single score

To conclude on virgin PLA, the base material has significant importance on the different EF impact categories results. Depending on (i) the environmental issues of the region of production, (ii) the availability of biowaste, and its water, sugar and lignocellulosic content, and (iii) the process waste valorisation, biowaste or crops can be more or less advantageous when used as primary biotic resources. Table 22 summarises which base bioproduct can be used and in which context.

Table 22 Overview of virgin PLA production hotspots analysis results and recommendations, Single score

Base bioproduct	Hotspots-Impact categories	Hotspots-Process contribution	Recommendations	Limits of the analysis
Maize	Climate Change Resource Use, fossils	Maize production	Check if supply country does not	This data is based on data from 2007 and

Base bioproduct	Hotspots- Impact categories	Hotspots- Process contribution	Recommendations	Limits of the analysis
	Particulate matter Water Use Acidification Resource Use, minerals and metals Photochemical ozone formation	Electricity and heat	have issues on water supply Prefer countries with a low impact grid mix	does not include sulfuric acid as an input, even though it is used for LA extraction
Sugarcane	Particulate matter Acidification Resource Use, minerals and metals Eutrophication, marine Eutrophication, terrestrial Water Use	Sugarcane production Electricity production by bagasse burning Sulfuric acid	Avoid energy co-production by bagasse burning when supply country is highly polluted	This data is based on a specific process where PLA is co-produced with ethanol, electricity and gypsum
Biowastes	Climate Change Resource Use, fossils Resource Use, minerals and metals Particulate matter Photochemical ozone formation Acidification	Electricity and heat	Biowaste quality can highly impact on the process yield: prefer low humidity and high carbohydrate/starch content. Prefer countries with a low impact grid mix	This data is based on process based on maize and a simple scaling factor based on biowaste composition (yields from literature) was applied. Ask for more specific data or confirm LCA methodology with potential supplier.
Fruit sugarcane	Climate Change Acidification Ecotoxicity, freshwater Eutrophication, terrestrial Particulate matter Resource Use, minerals and metals Resource Use, fossils	Industrial composting of process wastes Electricity and heat Sulfuric acid	Biowaste needs to be composed of fruits only Process organic waste needs to be valorised directly in fields or by home composting. Prefer countries with a low impact grid mix	Electricity and heat amount is not precise This process is limited to biowaste of fruits only where free sugars are available. This data is based on process based on sugarcane, with the same process yield. Ask for more specific data or confirm LCA methodology with potential supplier.

However, when recycling PLA, Figure 37 and Figure 38 show that the environmental impacts of the recycling process are lower than for producing virgin PLA. The inventories for this analysis were retrieved from D5.1.

As stipulated in D5.1, to use mechanically recycled PLA, it is necessary to mix it with 50% virgin PLA (here, considered from maize, ecoinvent 3.10 data) to preserve satisfactory mechanical properties. Therefore, as seen in Figure 37, the main impact of the production of mechanically recycled PLA comes from the virgin material ratio, which accounts for 96% of the single score impact result.

For chemically recycled PLA, the mechanical properties are as good as virgin PLA because the polymer is depolymerised into lactic acid (here, a hydrolysis is considered), to be polymerised again afterwards. Thus, chemically recycled PLA and virgin PLA have the same quality. Figure 38 shows that the impacts come mainly from the hydrolysis step. Figure 39 shows that the energy consumption during

hydrolysis is needed for heating the water (to 100-200°C) and for downstream processes (reactor heat losses)[40].

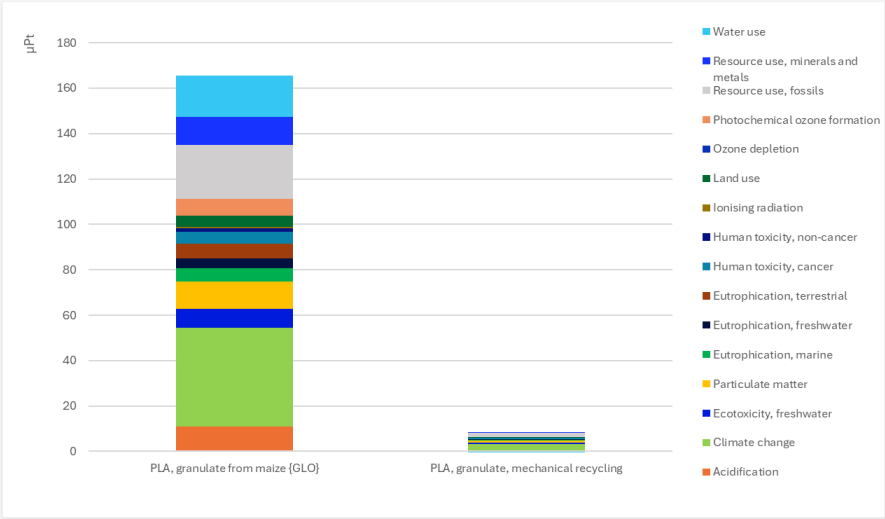


Figure 37 Mechanically recycled PLA, environmental impacts (EF3.1), Single score, 1kg

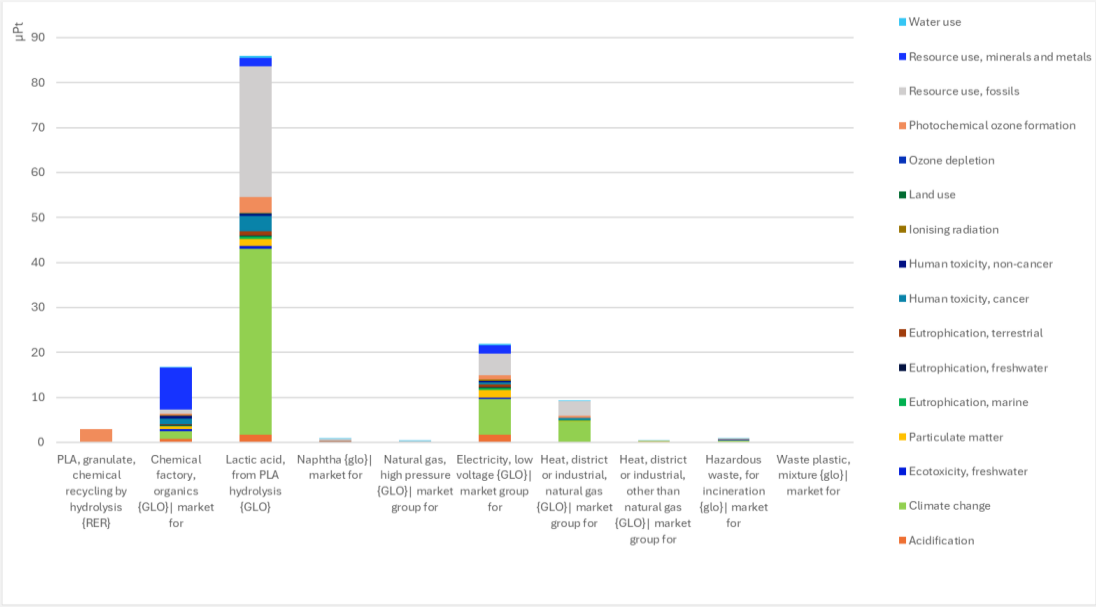


Figure 38 Chemically recycled PLA, environmental impacts (EF3.1), Single score

[40] (Piemonte et al., 2013) Chemical Recycling of PLA: A Great Opportunity Towards the Sustainable Development? | Journal of Polymers and the Environment

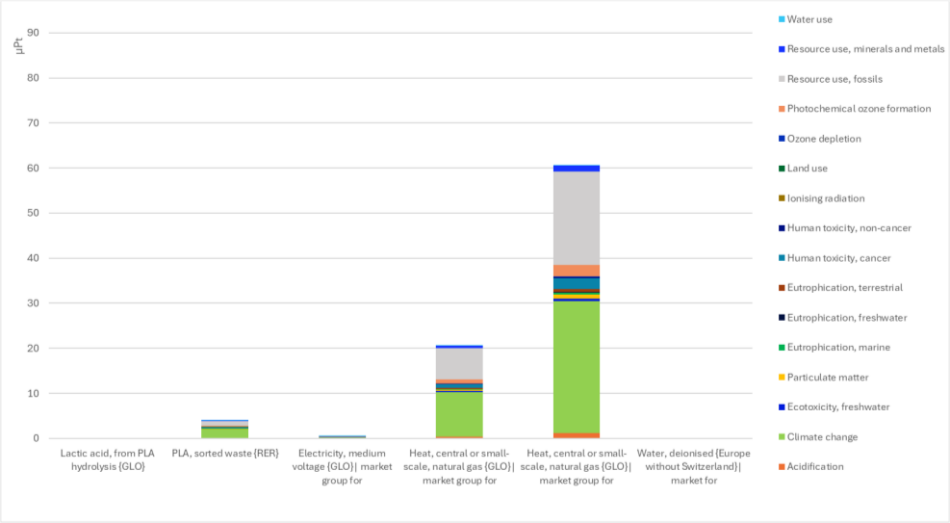


Figure 39 Lactic acid production from PLA hydrolysis, environmental impacts (EF3.1), Single score

To conclude, based on this analysis with EF3.1 and inventories taken and adapted from literature, the least impactful PLA material is recycled PLA, chemically or mechanically recycled. However, PLA material based on biowaste or on crops can also present some advantages compared to virgin PLA, and the recommendations are summarised in Table 22. It can also be noted that a mechanically recycled PLA, when combined with an optimised virgin PLA, could result in very low impacts. It is therefore essential to select a PLA supplier carefully.

In the following sections, “PLA” will always refer to PLA synthesised from maize, ecoinvent 3.10 cut-off dataset. Indeed, the dataset and inventory of this PLA is considered the most reliable, as it is not built from several references and comes from industrial data, even if it has not been reviewed recently. This data was used to model every PLA-based solution.

b) PLA-based solution materials

A great amount of identified solutions is based on PLA. Three of them are solely composed of PLA and will be studied in this section as their hotspots are similar.

(1) Oil and water PLA container materials

PLA bottles could be a solution to contain liquids such as oil (in the food kit) and water (in the WASH kit). Contrary to what was mentioned in D5.1 (capacity of 1L), 2L bottles will be used for oil and for water. To produce these bottles (2L), PLA is extruded and blow moulded. According to the provider of the solution, this material is industrially compostable.

The LCIA results with EF3.1 methodology highlight seven hotspots for this manufactured material:

Table 23 PLA Oil and water container LCIA, impact categories hotspots and results: PLA bottles, 1 kg

Midpoint impact categories (EF3.1, hotspots 80%)	Unit	Value for 1kg	Contribution (%)	Hotspots, process contribution (80%)
Climate Change	kg CO_2 eq	6,44E+00	32,43	PLA (electricity and heat) > Transformation > EoL
Resource Use, fossils	MJ	6,79E+01	15,7	PLA (heat and electricity) > Transformation
Water Use	m^3 world eq	6,24E+00	8,36	PLA (maize)
Particulate matter	disease incidence	2,89E-07	7,86	PLA (maize and electricity) > Transformation
Acidification	mol H^+ eq	3,38E-02	6,82	PLA (maize and electricity) > Transformation
Resource Use, minerals and metals	kg Sb equivalents	2,48E-05	5,31	PLA (factory, electricity and maize)
Photochemical ozone formation	kg NMVOC equivalents	2,05E-02	4,34	PLA (electricity and maize) > Transformation
Ecotoxicity, freshwater	CTUe	6,63E+01	4,05	PLA (maize) > EoL
Land Use	dimensionless (pt)	1,41E+02	2,46	PLA (maize) > Transformation
Eutrophication, freshwater	kg P eq	6,13E-04	1,93	PLA (wastewater, maize and electricity)

From the table above and graphs presented in Figure 40 and Figure 41, the most impactful processes are:

- Polylactic acid (PLA, bio-based) production, from maize grain (see section V.B.3.a)
- And plastic transformation by extrusion and blow moulding (see section V.B.1)

PLA-related impacts can vary depending on its biotic resource and production process (cf. Table 22). In any case, energy is a hotspot for PLA production, which contributes to impacts on Climate Change, Resource Use, fossils, Particulate matter, Resource Use, minerals and metals, as well as Photochemical ozone formation in this case. Maize crop agriculture, on the other hand, contributes to Water Use, Acidification, Ecotoxicity and Eutrophication of freshwater, Land Use, and to energy-related impacts. Depending on the biotic raw material, the impacts of agriculture can differ and the energy requirements for PLA synthesis can vary. See Table 22 for more details on the matter.

It can be noted that EoL has non-negligible impacts compared to the rest of the material life cycle, even if it is smaller. Impacts on Climate Change come from biogenic methane (CH_4) emissions at the EoL of plastics. The scenario for EoL degradation is described in IV.B. Process material loss (scraps) are treated as biowaste industrial composting, but this does not have significant impact.

No credits can be associated with PLA bottles EoL as PLA does not contain any of the fertilising elements N, P, or K. However, PLA in compost improves the structure of the soil and carbon content:

- PLA particles can help aerate the soil, improving water retention and drainage by creating soil aggregates that bind organic and inorganic substances. This can therefore enhance root development and microbial activity.[41]
- PLA is derived from renewable resources and, when composted, it contributes organic carbon, which is beneficial for soil microbial life and long-term soil fertility (see carbon uptake consideration in V.B.3.j)(2). It also fosters nitrogen fixation and denitrification, related to soil fertility and structure.[42]

To conclude, PLA bottles used as oil containers in food or WASH kits are impactful mainly at the production (raw materials and transformation) stage. The impacts of EoL by industrial compost focus on Climate Change and freshwater Ecotoxicity, even if it represents less than 15% of the overall impacts.

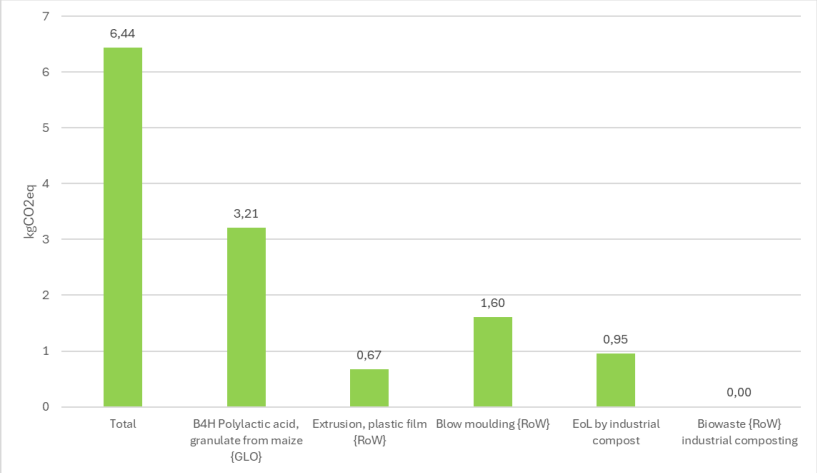


Figure 40 PLA Oil and water container LCIA, Climate Change results: PLA bottles, 1 kg

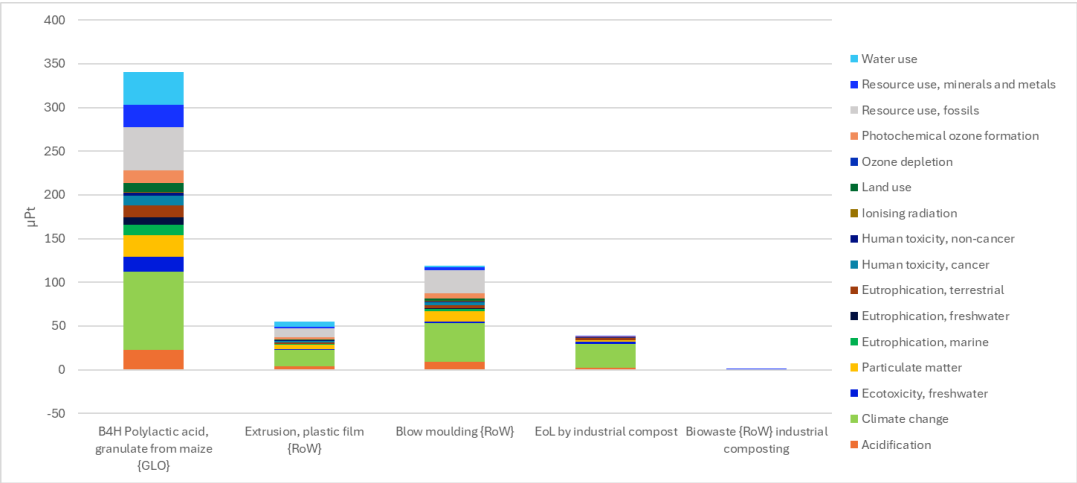


Figure 41 PLA Oil and water container LCIA, Single score results: PLA bottles, 1 kg

[41] Biodegradable microplastics coupled with biochar enhance Cd chelation and reduce Cd accumulation in Chinese cabbage | Biochar

[42] Distinct Influence of Conventional and Biodegradable Microplastics on Soil Microorganisms and Nitrogen Cycling: Emphasizing the Effect of Biodegradable Polylactic Acid | Water, Air, & Soil Pollution

An alternative to PLA is PHBV (Poly(3-Hydroxybutyrate-co-3-Hydroxyvalerate)), as mentioned in D5.1. Indeed, this bioplastic is biodegradable under any condition and does not need higher temperatures to degrade, as PLA does. This would then offer interesting properties for EoL management. However, its biodegradable properties can induce migration in food products, and PHBV food packaging remains a niche compared to PLA[43].

The single score results for PHBV production displayed in Figure 42 shows that most impacts are due primarily to PHBV material and blow moulding. Impacts related to the raw material come from the obtention of sugar from sugarcane, and secondly, from the energy use. The hotspots of PHBV bottles are similar to those of PLA bottles, but another issue in terms of Ecotoxicity, freshwater appears, because of sugar synthesis from sugarcane.

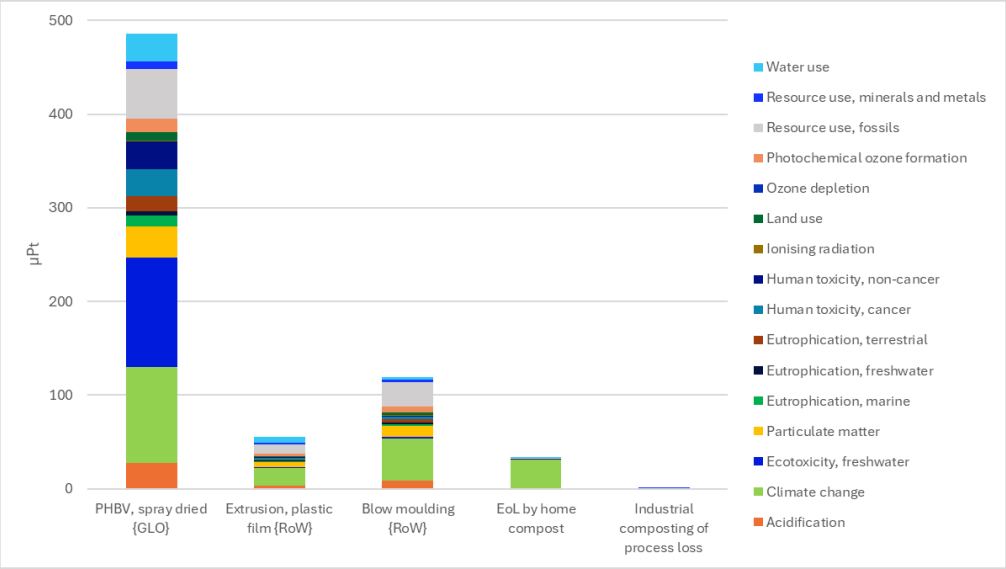


Figure 42 PHBV from sugarcane environmental impacts (EF3.1), Single score

(2) Biodegradable mosquito nets

Mosquito nets can be manufactured from PLA, as demonstrated in WP4. For this solution it is specified that PLA is manufactured from maize grain. At EoL, the solution is industrially compostable and is biodegradable in marine water but not in freshwater. As the countries of study, DRC and SS, do not have any marine coasts, mosquito net material EoL is considered to be industrial compost, and the inventory does not reflect that the impact on marine waters is limited thanks to this solution.

The LCIA results with EF3.1 methodology highlight eight hotspots for this manufactured material:

[43] PHBV-based polymers as food packaging: Physical-chemical and structural stability under reuse conditions

Table 24 Biodegradable mosquito nets LCIA, impact categories hotspots and results: PLA net, 1 kg

Midpoint impact categories (EF3.1, hotspots 80%)	Unit	Value for 1kg	Contribution (%)	Hotspots, process contribution (80%)
Climate Change	kg CO_2 eq	4,70E+00	30,68	PLA (electricity and heat) > EoL
Resource Use, fossils	MJ	4,61E+01	13,82	PLA (heat and electricity)
Water Use	m^3 world eq	5,10E+00	8,86	PLA (maize)
Resource Use, minerals and metals	kg Sb eq	2,89E-05	8,01	PLA (factory, electricity and maize) > Weaving
Particulate matter	disease incidence	2,01E-07	7,08	PLA (maize and electricity)
Acidification	mol H^+ eq	2,57E-02	6,7	PLA (maize and electricity) > Weaving
Ecotoxicity, freshwater	CTUe	6,08E+01	4,82	PLA (maize)
Photochemical ozone formation	kg NMVOC eq	1,49E-02	4,08	PLA (electricity maize and heat)
Land Use	dimensionless (pt)	1,06E+02	2,41	PLA (maize)
Eutrophication, freshwater	kg P eq	5,36E-04	2,19	PLA (wastewater, maize and electricity)

From the graphs presented in Figure 43 and Figure 44, the most impactful processes are:

- Polylactic acid (PLA, bio-based) production (from maize grain)
- EoL by industrial composting.

Please refer to V.B.3.a) and V.B.3.b)(1) for more information on PLA and EoL impacts.

To conclude, mosquito nets are impactful, mainly due to PLA production, as are the other PLA-based solutions. Choosing the correct PLA can help mitigate the impact of this packaging material, as mentioned in V.B.3.a). EoL by industrial compost impacts Climate Change only, but is not significant compared to other impact categories such as fossil Resource Use.

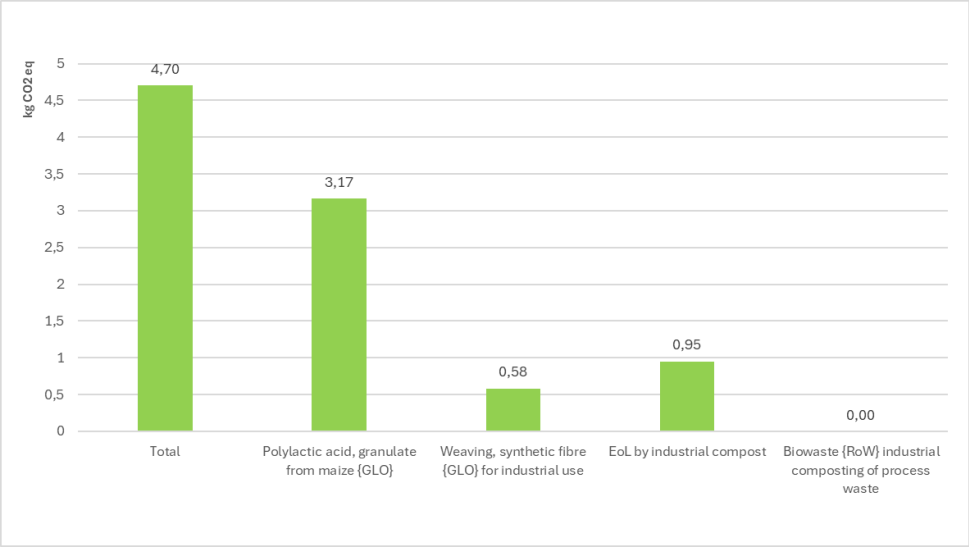


Figure 43 Biodegradable mosquito nets LCIA, damage assessment Climate Change: PLA net, 1 kg

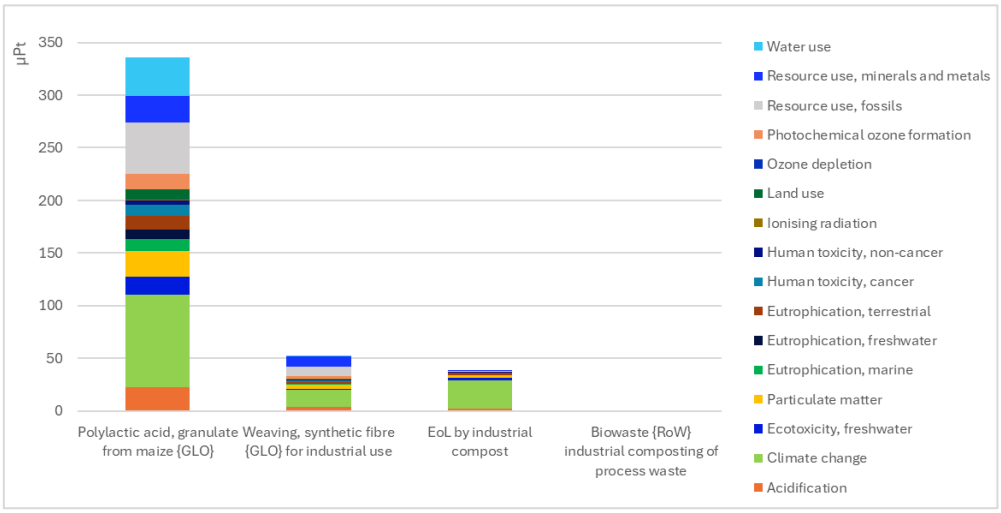


Figure 44 Biodegradable mosquito nets LCIA, Single score: PLA net, 1 kg

(3) Biodegradable laminating film

Biodegradable film aims to replace PE film used for tertiary packaging. It corresponds to a PLA extruded film. This material is industrially compostable.

The LCIA results with EF3.1 methodology highlight eight hotspots for this manufactured material:

Table 25 Biodegradable laminating film LCIA, impact categories hotspots and results: PLA film, 1 kg

Midpoint impact categories (EF3.1, hotspots 80%)	Unit	Value for 1kg	Contribution (%)	Hotspots, process contribution (80%)
Climate Change	kg CO_2 eq	4,52E+00	30,47	PLA (electricity and heat) > EoL
Resource Use, fossils	MJ	4,59E+01	14,19	PLA (heat and electricity)
Water Use	m^3 world eq	5,88E+00	10,54	PLA (maize)
Particulate matter	disease incidence	1,85E-07	6,71	PLA (maize and electricity)
Acidification	mol H^+ eq	2,43E-02	6,54	PLA (maize and electricity)
Resource Use, minerals and metals	kg Sb eq	2,21E-05	6,35	PLA (factory, electricity and maize)
Ecotoxicity, freshwater	CTUe	6,04E+01	4,94	PLA (maize) > EoL
Photochemical ozone formation	kg NMVOC eq	1,42E-02	4,02	PLA (electricity maize and heat)
Land Use	dimensionless (pt)	1,12E+02	2,63	PLA (maize)
Eutrophication, freshwater	kg P eq	5,37E-04	2,26	PLA (wastewater, maize and electricity)

From the graphs presented Figure 45 and Figure 46, the most impactful processes are:

- Polylactic acid (PLA, bio-based) production (from maize grain)
- And EoL by industrial composting.

Please refer to V.B.3.a) and V.B.3.b)(1) for more information on PLA and EoL impacts.

As for the other PLA-based solutions, biodegradable laminating film as tertiary packaging is impactful, mainly due to PLA production, but its impact can be mitigated, as explained in previous sections.

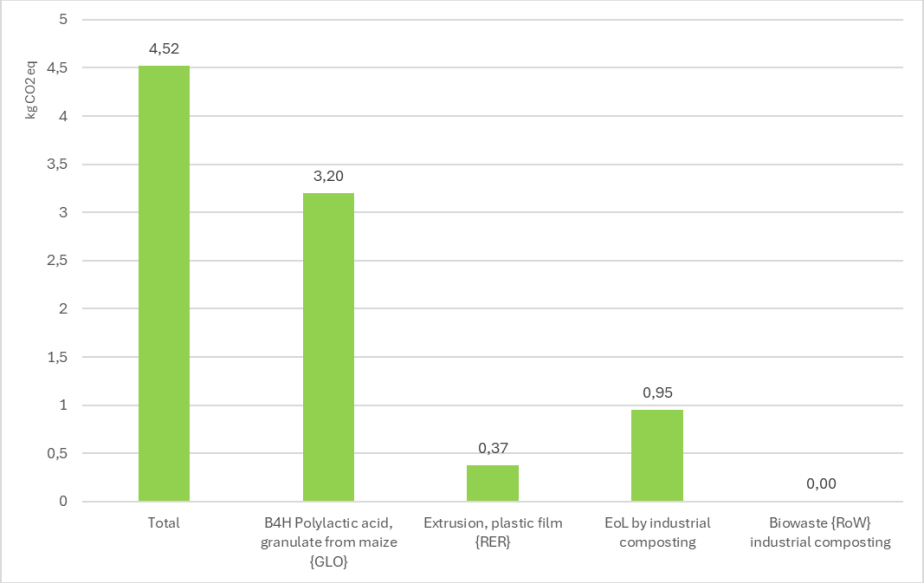


Figure 45 Biodegradable laminating film LCIA, damage assessment Climate Change: PLA film, 1 kg

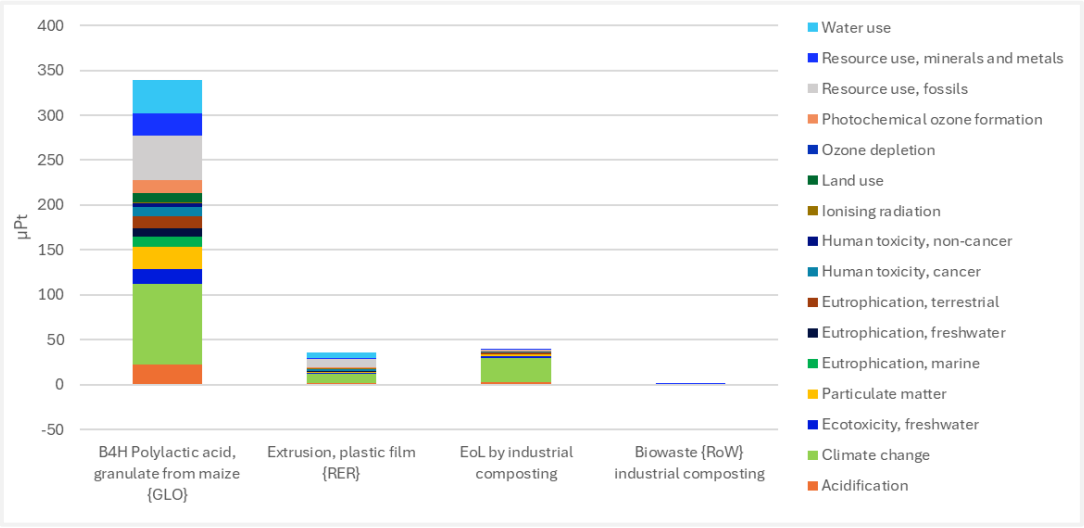


Figure 46 Biodegradable laminating film LCIA, Single score: PLA film, 1 kg

c) Compostable pouch for RUTF materials

To contain Ready-to-use therapeutic foods (RUTF), a multi-material packaging film is used. A solution was found in WP4 with cellophane, PUR adhesive, PBAT, PLA, and metallic cellulose layers to ensure RUTF packaging. The impacts of 1kg of such packaging are studied in the following paragraphs. This material is home compostable.

The LCIA results with EF3.1 methodology highlight seven hotspots for this manufactured material:

Table 26 Compostable pouch for RUTF LCIA, impact categories hotspots and results: 1 kg

Midpoint impact categories (EF3.1, hotspots 80%)	Unit	Value for 1kg	Contribution (%)	Hotspots, process contribution (80%)
Climate Change	kg CO_2 eq	7,96E+00	34,04	Met. Cellulose > PBAT > PLA
Resource Use, fossils	MJ	9,65E+01	18,93	Met. Cellulose > PBAT
Particulate matter	disease incidence	3,98E-07	9,18	Met. Cellulose > PBAT > cellophane
Acidification	mol H^+ eq	3,90E-02	6,66	Met. Cellulose > PBAT > PLA
Water Use	m^3 world eq	5,52E+00	6,28	PBAT > PLA > Met. Cellulose
Resource Use, minerals and metals	kg Sb eq	2,57E-05	4,67	PLA (factory, electricity and maize)
Photochemical ozone formation	kg NMVOC eq	2,39E-02	4,29	Met. Cellulose > PBAT > PLA
Ecotoxicity, freshwater	CTUe	5,27E+01	2,74	Met. Cellulose > PLA > PBAT
Land Use	dimensionless (pt)	1,19E+02	1,77	Met. Cellulose > PLA > cellophane
Eutrophication, freshwater	kg P eq	4,73E-04	1,26	Met. Cellulose > PLA > PBAT

From the graphs presented in Table 26 above and Figure 47 and Figure 48, the most impactful processes are:

- Metallised cellulose production
- PBAT (Polybutylene adipate terephthalate) production
- PLA (see section V.B.3.a) and V.B.3.b)(1))
- EoL by home composting (see section IV.B.2)

An analysis of the metallised cellulose production shows that impacts are mostly due to physical vapour deposition of copper, which is mainly impactful due to electricity consumption.

PBAT impacts represented by *1,4-butanediol {GLO}| market for* dataset come from heat input, and reactants (formaldehyde and acetylene) for 1,4-butanediol production, monomer for PBAT production. This data could be improved by the input of the polymerisation process and the use of other monomers (adipic acid and dimethyl terephthalate), but monomer production was used as a proxy.

To conclude, compostable pouch solution materials for the food kit have a significant impact mainly at the raw materials production stage. Impacts of EoL by home composting in heaps are part of the main contributors to Climate Change.

Credits associated with compostable pouch EoL are soil nutrition due to N content in the PUR layer (calculation details are presented in Annex VIII.B.2.f). Single score credits result with EF3.1 is 0.98µPt. Other layers do not contain any N, P or K. These credits are not included in the material results of Figure 47 and Figure 48 for methodological reasons (EF3.1).

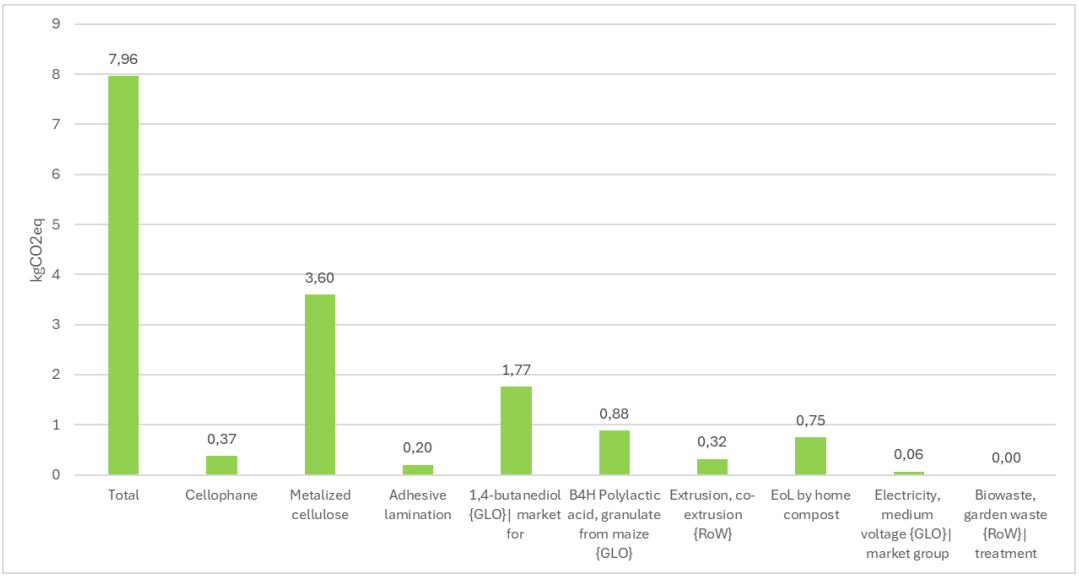


Figure 47 Compostable pouch for RUTF LCIA, Climate Change results : 1 kg

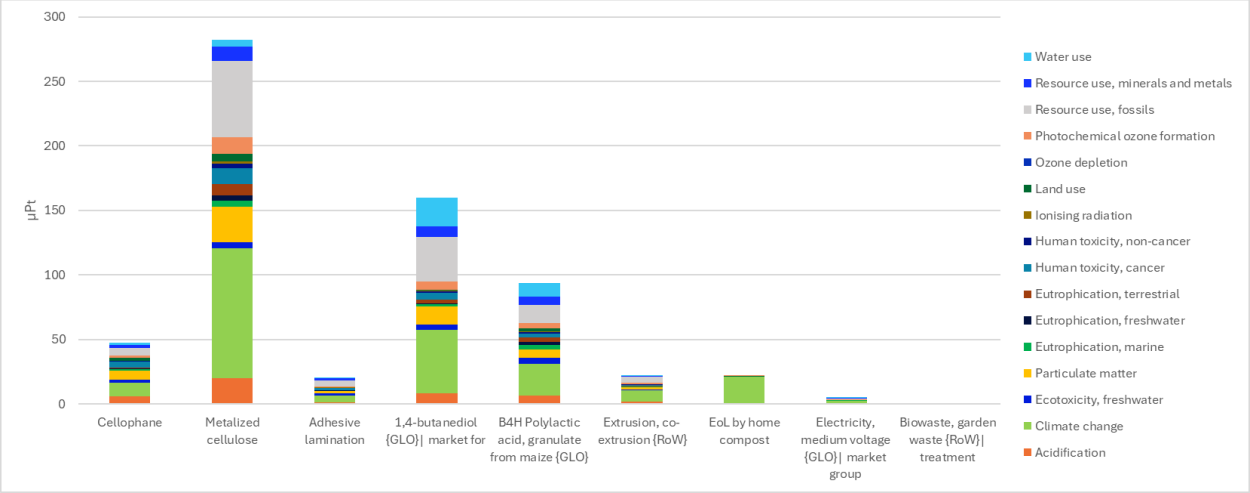


Figure 48 Compostable pouch for RUTF LCIA, Single score results: 1 kg

d) Disposable bag from renewable resources, for primary packaging materials

Disposable bags from renewable resources are considered to replace PE liner and PP bags for primary packaging of the items mentioned in V.B.2.d). These bags are made of polyester made of starch. This material is industrially compostable.

The LCIA results with EF3.1 methodology highlight six hotspots for this manufactured material:

Table 27 Disposable bag from renewable resources, LCIA, impact categories hotspots and results: 1 kg

Midpoint impact categories (EF3.1, hotspots 80%)	Unit	Value for 1kg	Contribution (%)	Hotspots, process contribution (80%)
Climate Change	kg CO_2 eq	4,13E+00	33,17	Polyester > EoL
Resource Use, fossils	MJ	5,79E+01	21,35	Polyester

Midpoint impact categories (EF3.1, hotspots 80%)	Unit	Value for 1kg	Contribution (%)	Hotspots, process contribution (80%)
Particulate matter	disease incidence	2,29E-07	9,92	Polyester
Acidification	mol H^+ eq	2,11E-02	6,79	Polyester > Transformation
Resource Use, minerals and metals	kg Sb eq	1,81E-05	6,19	Polyester
Photochemical ozone formation	kg NMVOC eq	1,36E-02	4,57	Polyester > Transformation
Water Use	m^3 world eq	1,63E+00	3,47	Polyester
Ecotoxicity, freshwater	CTUe	3,02E+01	2,95	Polyester > EoL
Land Use	dimensionless (pt)	4,01E+01	1,12	Polyester
Eutrophication, freshwater	kg P eq	1,73E-04	0,87	Polyester > Transformation

From the table above and graphs presented in Figure 49 and Figure 50, the most impactful processes are:

- Starch-based polyester (bio-based) production
- EoL by industrial composting. (see section IV.B.2)

Polyester-related impacts are due to heat (other than natural gas), which contributes to impacts on Climate Change, Particulate matter, Resource Use, and fossils, as well as Photochemical ozone formation. Maize starch production also contributes to Climate Change, Water Use, Resource Use of fossils and minerals and metals, Particulate matter, and Acidification.

No credits can be associated with polyester starch material EoL as it is not composed of any of the fertilising elements N, P, or K. However, as for PLA, polyester is a source of carbon for soil microorganisms and it can improve soil biological activity, which indirectly benefits soil health. This material can improve soil structure, contribute to water retention and promote aggregate formation.

Electricity input corresponds to the energy needs of the transformation process.

To conclude, disposable bags from renewable resources used as primary materials in the kits are mainly impactful at the production (raw materials) stage. The impacts of EoL by industrial compost are only relevant for Climate Change and freshwater Ecotoxicity.

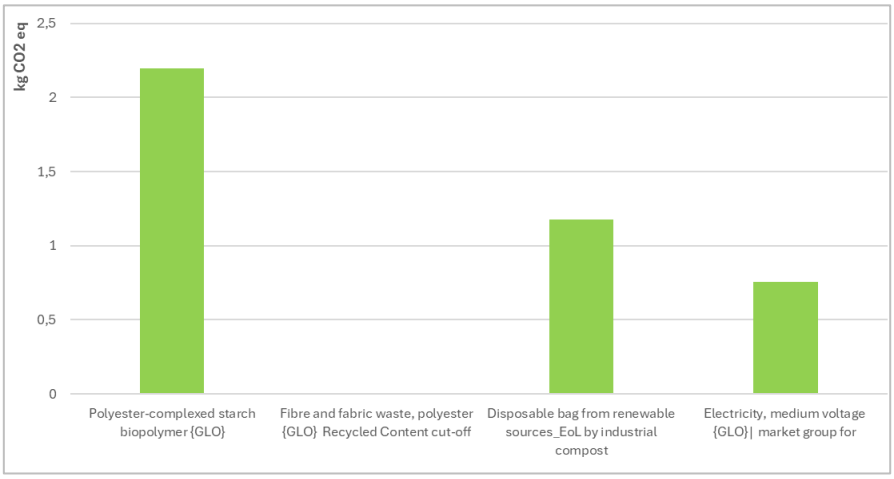


Figure 49 Disposable bag from renewable resources LCIA, Climate Change results: 1 kg

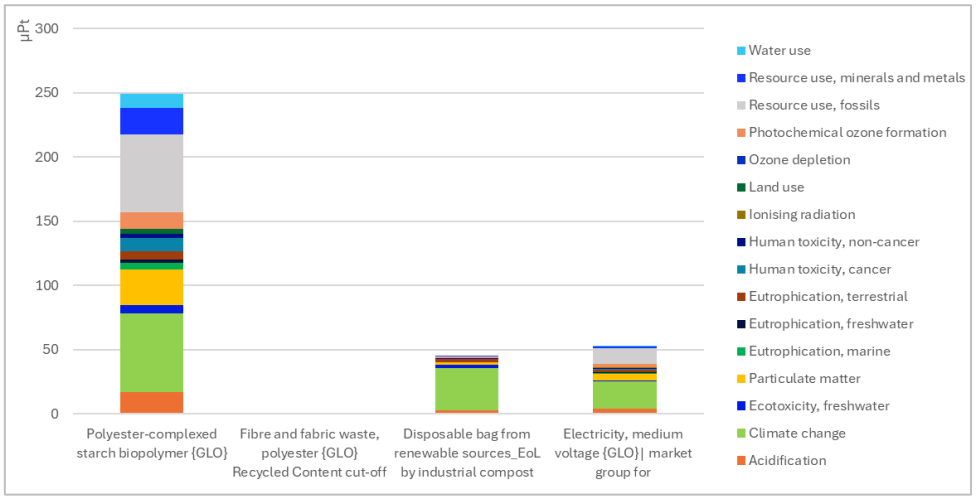


Figure 50 Disposable bag from renewable resources LCIA, Single score results: 1 kg

e) Compostable disposable pads with wings

Biobased pads are made of cotton as the main material, an absorbent layer, and starch biopolymer as the barrier layer. They are considered home compostable.

The LCIA results with EF3.1 methodology highlight four hotspots for this manufactured material:

Table 28 Compostable pads LCIA, impact categories hotspots and results: 1 kg

Midpoint impact categories (EF3.1, hotspots 80%)	Unit	Value for 1kg	Contribution (%)	Hotspots, process contribution (80%)
Eutrophication, freshwater	kg P eq	1,14E-02	38,56	Cotton fibre
Eutrophication, marine	kg N eq	7,75E-02	22,69	Cotton fibre
Land Use	dimensionless (pt)	6,63E+02	12,42	Cotton fibre
Climate Change	kg CO_2 eq	1,88E+00	10,11	EoL > Cotton
Resource Use, fossils	MJ	7,53E+00	1,86	Electricity > Starch biopolymer

Midpoint impact categories (EF3.1, hotspots 80%)	Unit	Value for 1kg	Contribution (%)	Hotspots, process contribution (80%)
Ecotoxicity, freshwater	CTUe	5,50E+00	0,36	Cotton > starch biopolymer
Water Use	m^3 world eq	1,32E-01	0,19	Starch biopolymer > Electricity

From the table above and the figures below, the most contributing processes are:

- Cotton fibre
- EoL (home composting) (see section IV.B.2)
- Electricity

Cotton fibre has a significant impact on most relevant categories, as the cultivation of cotton affects Land Use, Eutrophication, and Ecotoxicity.

The electricity use from the production process is a contributor to the use of fossil resources.

No credits can be associated with cotton or polymer starch material EoL, as it is not composed of any of the fertilising elements N, P, or K. However, as the other bio-based material, it provides structural advantages for biomass, which is not accounted for by credits assessment methodology itself.

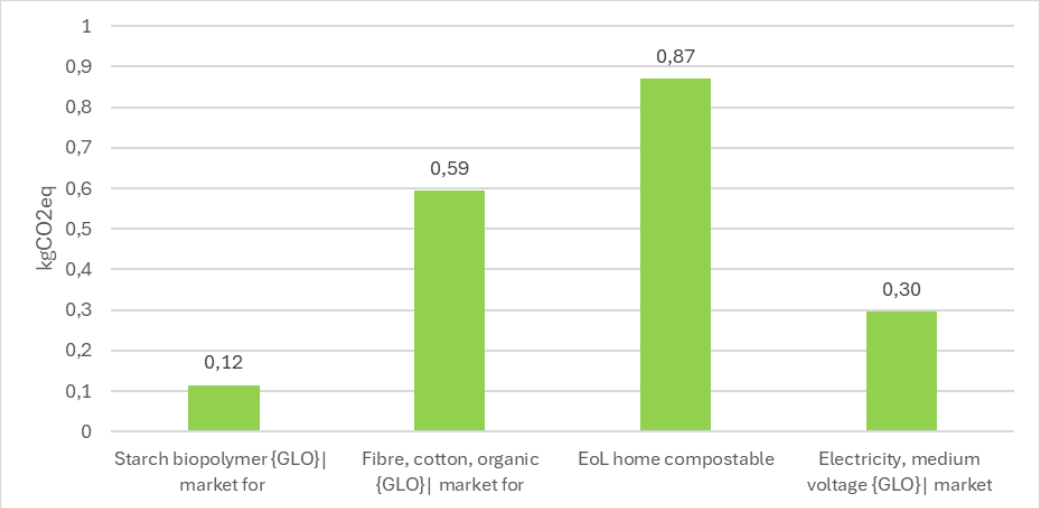


Figure 51 Compostable pads LCIA, Climate Change results: 1 kg

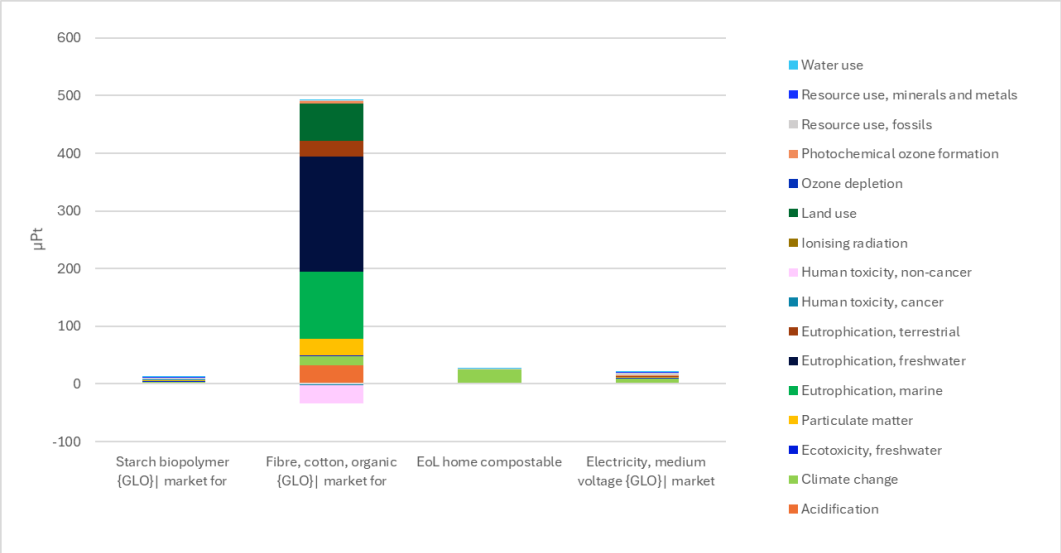


Figure 52 Compostable pads LCIA, single score results: 1 kg

f) Bio-based adhesive tape

Biobased adhesive tape is composed of PLA and a natural rubber seal. It is considered home compostable.

The LCIA results with EF3.1 methodology highlight six hotspots for this manufactured material:

Table 29 Biobased Adhesive Tape LCIA, impact categories hotspots and results: 1 kg

Midpoint impact categories (EF3.1, hotspots 80%)	Unit	Value for 1kg	Contribution (%)	Hotspots, process contribution (80%)
Climate Change	kg CO_2 Eq	5,16E+00	27,16	PLA from maize > Natural rubber > Coating
Photochemical ozone formation	kg NMVOC eq	9,37E-02	20,68	Natural rubber
Resource Use, fossils	MJ	7,20E+01	17,40	PLA from maize > Natural rubber > Coating
Water Use	m^3 world eq	4,05E+00	5,68	PLA from maize
Particulate matter	disease incidence	1,66E-07	4,72	PLA from maize > natural rubber
Acidification	mol H^+ eq	2,15E-02	4,52	PLA from maize
Ecotoxicity, freshwater	CTUe	4,70E+01	3,00	PLA from maize > natural rubber
Eutrophication, freshwater	kg P eq	4,47E-04	1,47	PLA from maize > Coating
Land Use	dimensionless (pt)	8,02E+01	1,47	PLA from maize

From the table above and the figures below the most contributing processes are:

- PLA from Maize, which accounts for 68% of total mass (see section V.B.3.a) and V.B.3.b)(1))
- Natural rubber, 32% of adhesive tape composition
- Coating process (electricity and heat)

Natural rubber production emits non-methane volatile organic compounds, contributing to Photochemical ozone depletion. Chemicals needed to coagulate the natural rubber, as well as the electricity and heat needed for the processing explain the other impacts in Climate Change or Resource Use, fossils.

The electricity and heat used to produce the tape have impacts on Climate Change and the use of fossil Resources. Global dataset values were used, and a precise location could change those results.

The amount of credit associated with the tape is of 2 µPt because of the N content of natural rubber.

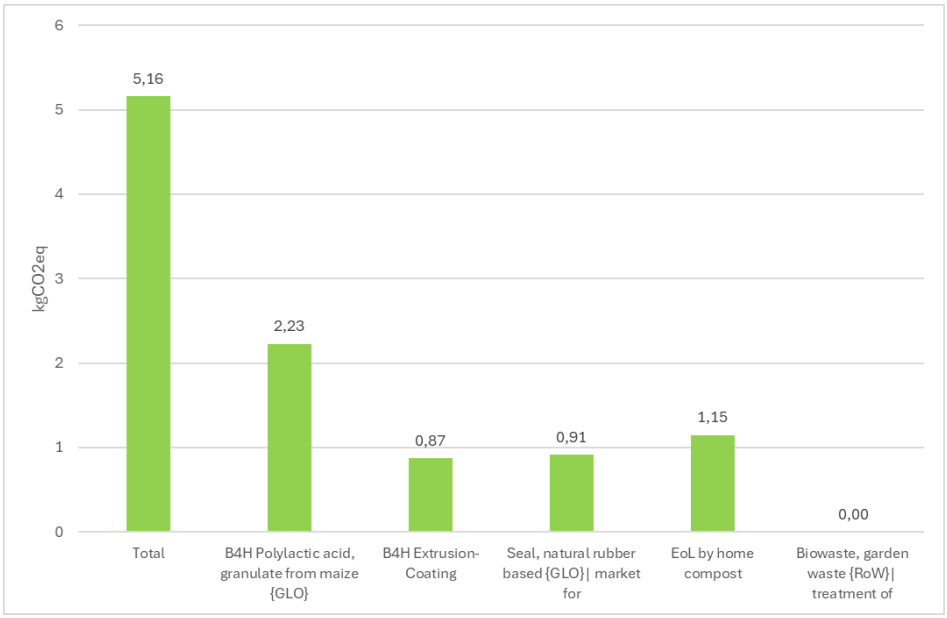


Figure 53 Biobased Adhesive Tape LCIA, Climate Change results: 1 kg

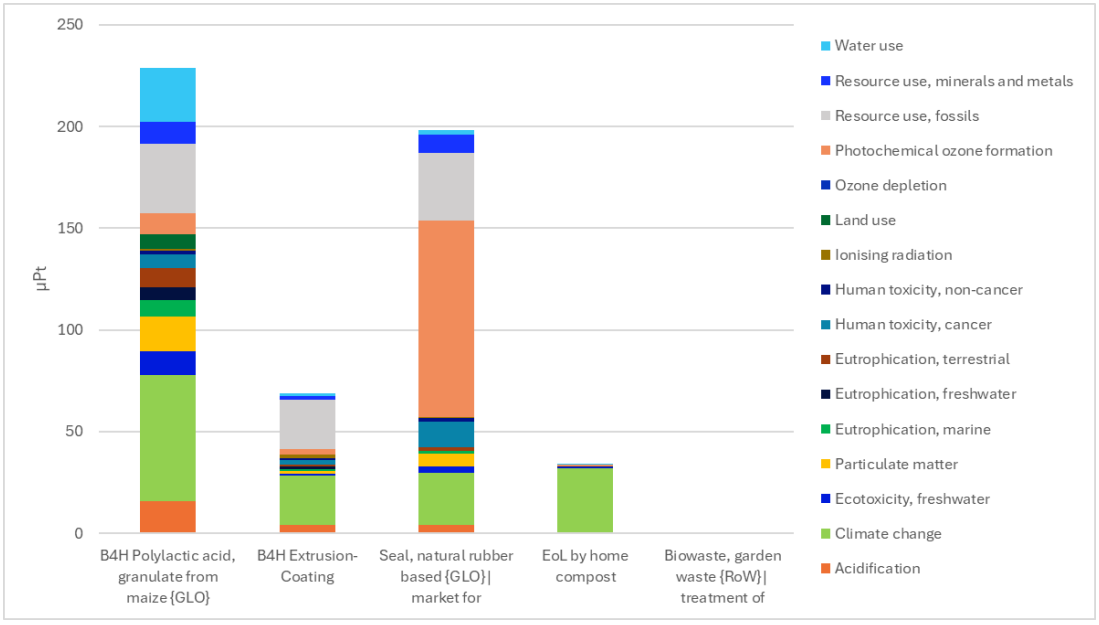


Figure 54 Biobased Adhesive Tape LCIA, single score results: 1 kg

g) Building insulation materials

Bio-PUR foam-, cellulose-, wool-, hemp-based insulation materials

(1) Biobased polyurethane

Bio-PUR foam is made from soybean oil. Even if it is a biobased material, it is not compostable, as PUR is a thermoset polymer. Thus, open burning is considered, and no credits are associated.

The LCIA results with EF3.1 methodology highlight eight hotspots for this manufactured material:

Table 30 Biobased PUR insulation LCIA, impact categories hotspots and results: 1 kg

Midpoint impact categories (EF3.1, hotspots 80%)	Unit	Value for 1kg	Contribution (%)	Hotspots, process contribution (80%)
Eutrophication, freshwater	kg P eq	2,24E-02	24,78	Soybean oil
Climate Change	kg CO_2 eq	9,42E+00	16,65	Toluene diisocyanate > soybean oil > EoL > hygrogen peroxyde
Photochemical ozone formation	kg NMVOC eq	1,01E-01	7,47	EoL > toluene diisocianate
Resource Use, fossils	MJ	9,05E+01	7,34	Toluene diisocyanate > hydrogen peroxide > Soybean oil
Ecotoxicity, freshwater	CTUe	3,13E+02	6,72	Soybean oil > EoL
Resource Use, minerals and metals	kg Sb eq	8,51E-05	6,40	Tin > Toluene diisocyanate
Acidification	mol H^+ eq	8,67E-02	6,13	EoL > toluene diisocianate
Eutrophication, terrestrial	mol N eq	3,88E-01	5,16	EoL
Water Use	m^3 world eq	1,04E+01	4,90	Water > hydrogen peroxide > toluene
Land Use	dimensionless (pt)	1,15E+02	0,71	Soybean oil

From the table above and the figures below, the most contributing processes are:

- Soybean production
- EoL (open burning) (see section IV.B.1)
- Toluene isocyanate (chemical)

Soybean oil production leads to Eutrophication of freshwater systems, due to nutrient runoff from fertilisers, and contributes to Ecotoxicity through pesticide use. The land occupation required for soybean cultivation is another driver of environmental burden. Greenhouse gas emissions from the production and processing of soybeans also add to the Climate Change impact of the insulation material. Overall, soybean oil represents a major hotspot in several environmental categories despite being a renewable input.

The chemical components used in the production of bio-PUR foam, particularly toluene diisocyanate (TDI) and other chemical additives, are responsible for a substantial share of environmental impacts. These chemicals contribute significantly to Climate Change, Photochemical ozone formation, Acidification, and

fossil Resource depletion due to their energy-intensive synthesis. Additionally, some chemical precursors can generate toxic emissions, which can affect freshwater Ecotoxicity.

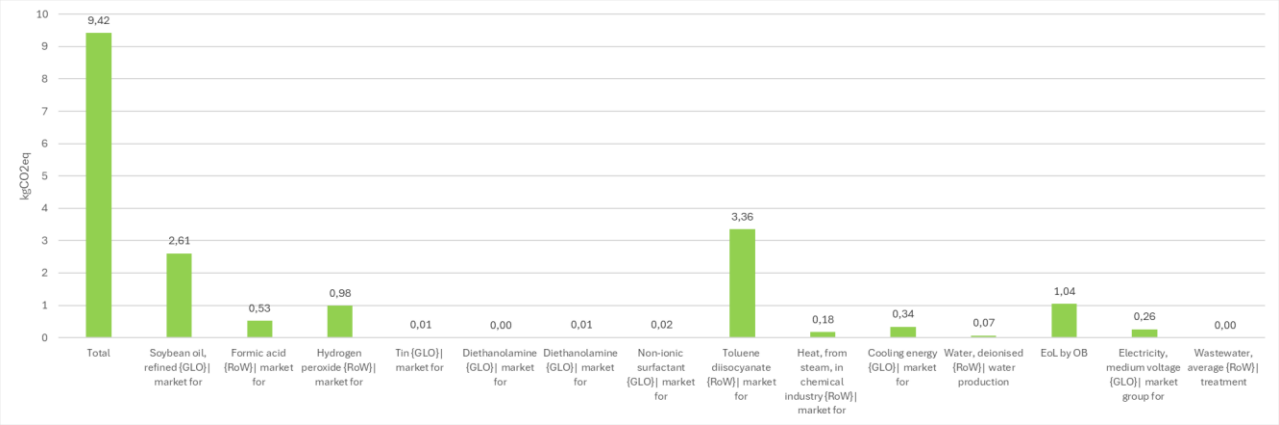


Figure 55 Biobased PUR insulation LCIA, Climate Change results: 1 kg

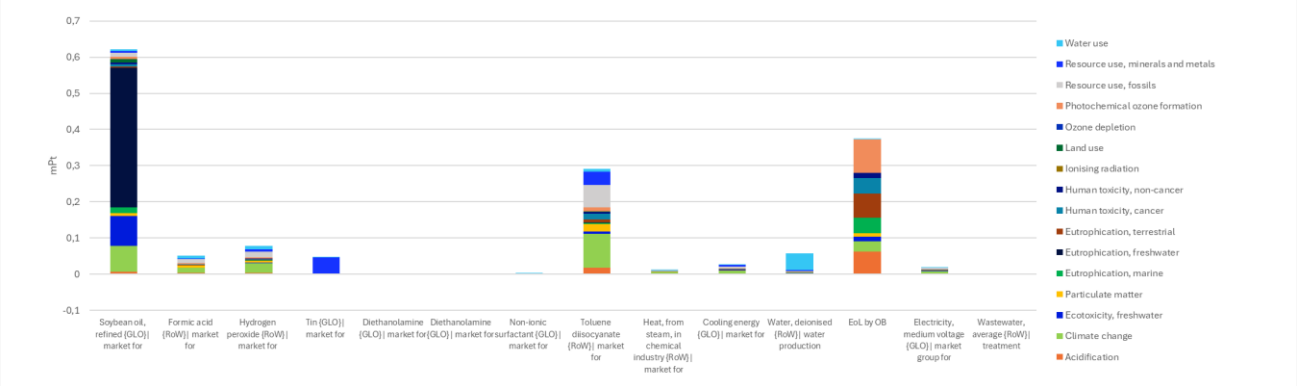


Figure 56 Biobased PUR insulation LCIA, single score results: 1 kg

(2) Hemp-based insulation

This insulation is made from hemp and PE fibres. Because of these fibres, it is considered incinerated at the EoL and not compostable.

The LCIA results with EF3.1 methodology highlight six hotspots for this manufactured material:

Table 31 Hemp based insulation LCIA, impact categories hotspots and results: 1 kg

Midpoint impact categories (EF3.1, hotspots 80%)	Unit	Value for 1kg	Contribution (%)	Hotspots, process contribution (80%)
Climate Change	kg CO_2 Eq	1,13E+00	29,28	Electricity > EoL
Resource Use, fossils	MJ	1,15E+01	13,57	Electricity
Human Toxicity, cancer	CTUh	9,59E-09	10,96	Solar energy > Electricity
Acidification	mol H^+ eq	9,83E-03	10,16	Direct emissions > EoL > Electricity
Eutrophication, terrestrial	mol N eq	5,04E-02	9,79	Direct emissions > EoL

Midpoint impact categories (EF3.1, hotspots 80%)	Unit	Value for 1kg	Contribution (%)	Hotspots, process contribution (80%)
Particulate matter	disease incidence	6,93E-08	9,66	Direct emissions > Electricity
Ecotoxicity, freshwater	CTUe	8,85E+00	2,77	EoL > Electricity
Land Use	dimensionless (pt)	4,48E+01	4,02	Land occupation to grow hemp
Eutrophication, freshwater	kg P eq	5,86E-05	0,94	Direct emissions > electricity
Water Use	m^3 world eq	-1,87E+00	-12,88	Direct emissions to water and soil > irrigation

From the table above and the figures below, the most contributing processes are:

- Electricity
- EoL (see section IV.B.1)
- Direct emissions

Electricity use during cultivation and manufacturing is the main hotspot, contributing substantially to both Climate Change and Resource Use, fossils. Solar energy used in growth also contributes marginally to Human Toxicity, cancer, reflecting emissions associated with land management and indirect electricity consumption in the supply chain.

Direct emissions from cultivation, processing, and irrigation affect Acidification, Eutrophication, Particulate matter formation, and Water Use. The Water Use indicator is negative, indicating a modelled net benefit in water flows, likely due to the water returning to the system exceeding the irrigation. Land occupation for hemp cultivation contributes to Land-use impacts, while trace emissions of metals or chemicals to soil and water have minor contributions to freshwater Ecotoxicity and Eutrophication.

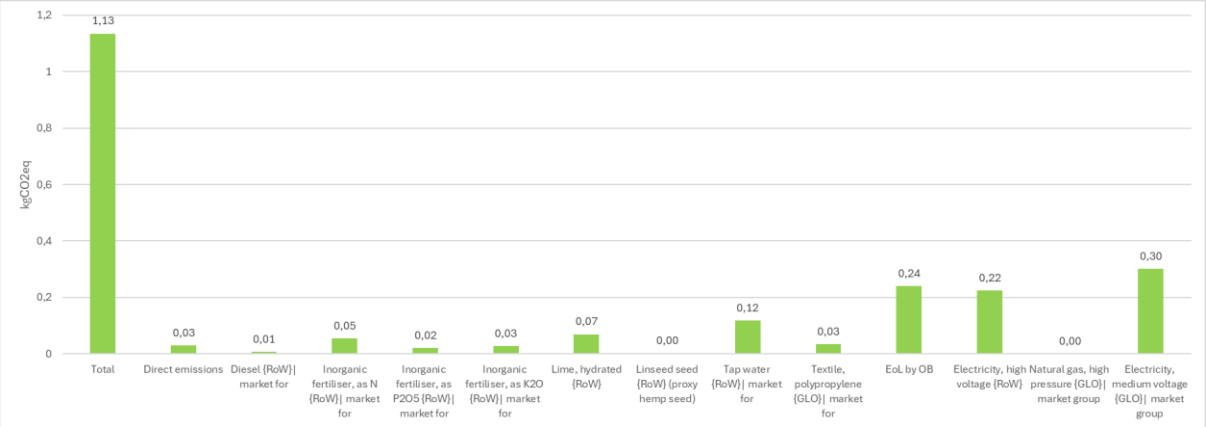


Figure 57 Hemp based insulation LCIA, Climate Change results: 1 kg

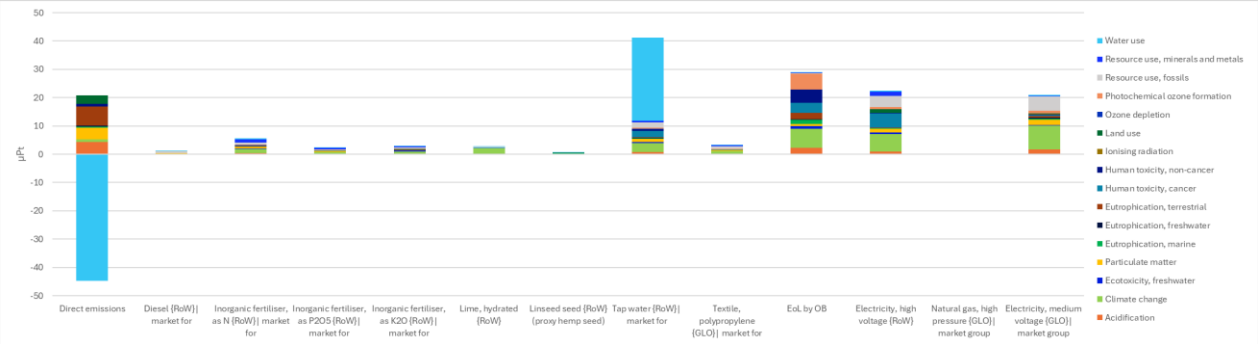


Figure 58 Hemp based insulation LCIA, single score results: 1 kg

(3) Sheep wool insulation

Sheep wool insulation is made of mineral wool from sheep. It is compostable, and as the carbon is considered mineral, there are no emissions of biogenic carbon or methane in the air, as it is sequestered in the soil. Our scenario considers that sheeps are fed with maize and soybean.

The LCIA results with EF3.1 methodology highlight five hotspots for this manufactured material:

Table 32 Sheep wool insulation LCIA, impact categories hotspots and results: 1 kg

Midpoint impact categories (EF3.1, hotspots 80%)	Unit	Value for 1kg	Contribution (%)	Hotspots, process contribution (80%)
Climate Change	kg CO_2 Eq	7,28E+00	21,04	Direct emission > maize grain > heat
Acidification	mol H^+ eq	1,64E-01	18,93	Direct emissions
Particulate matter	disease incidence	1,15E-06	18,00	Direct emissions
Eutrophication, terrestrial	mol N eq	7,21E-01	15,69	Direct emissions
Ecotoxicity, freshwater	CTUe	3,70E+02	12,99	Soybean meal
Resource Use, fossils	MJ	2,30E+01	3,05	Heat > Electricity
Eutrophication, freshwater	kg P eq	1,40E-03	2,52	Direct emissions
Water Use	m^3 world eq	6,45E-01	0,50	Water treatment > Direct emissions
Land Use	dimensionless (pt)	4,72E+01	0,47	Shed > Maize > soybean

From the table above and the figures below, the most contributing processes are:

- Direct emissions
- Maize grain
- Soybean meal

Direct emissions have a significant impact on Acidification, Climate Change, Particulate matter, and terrestrial Eutrophication. Sheep wool insulation exhibits significant environmental impacts, primarily due to livestock-related emissions. Climate Change is strongly driven by methane from enteric fermentation and by nitrous oxide from manure and pasture soils. Ammonia volatilisation from manure

is a significant source of both Acidification and Particulate matter formation. At the same time, the leaching of ammonia and nitrate into soils and groundwater leads to terrestrial Eutrophication, enriching ecosystems with nitrogen and disrupting biodiversity. Overall, the direct emissions of greenhouse gases and nitrogen compounds from sheep farming explain the dominant impacts difference compared to plant-based alternatives.

For maize grain as animal feed, the main reason for Climate Change is nitrous oxide emissions from fertilised agricultural soils, which have a very high global warming potential. Maize also shows negative values for Human Toxicity (non-cancerous), because some datasets are modelled as generating avoided emissions.

Soybean cultivation for animal feed is a hotspot for freshwater Ecotoxicity, primarily due to the use of pesticides and herbicides in soybean farming. In addition, heavy metal flows associated with fertiliser production and use may contribute to Ecotoxicity.

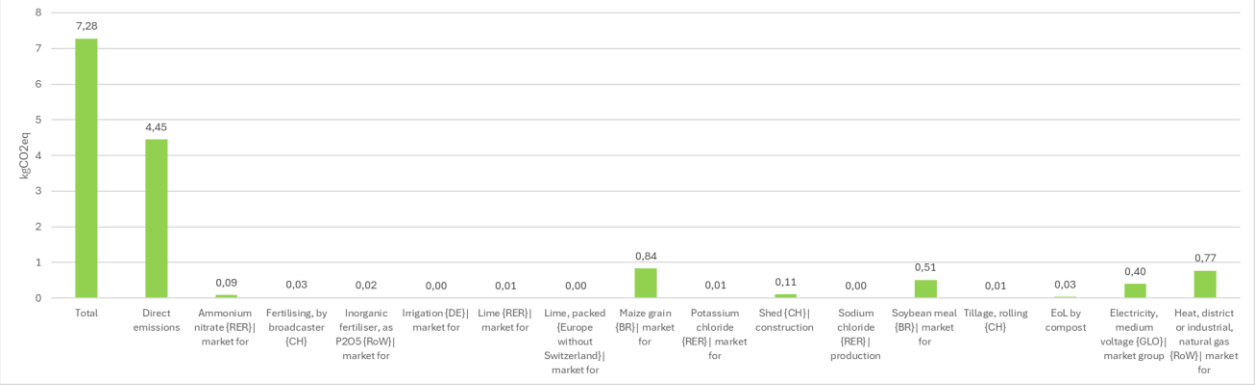


Figure 59 Sheep wool insulation LCIA, Climate Change results: 1 kg

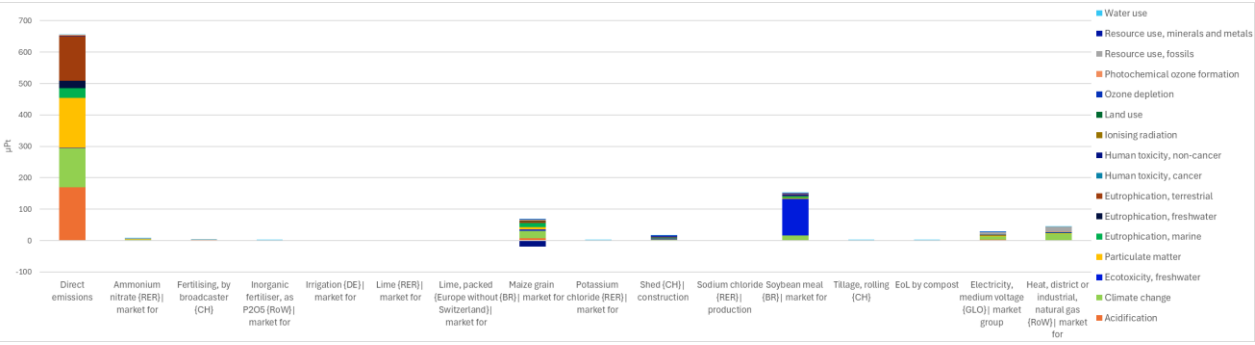


Figure 60 Sheep wool insulation LCIA, single score results: 1 kg

(4) Cellulose-based insulation

Cellulose insulation was not present in the deliverable D5.1 but it seems interesting due to its biobased nature and its connection to the CALIMERO EU Project. Its inventory can be found in Annex VIII.B.2.e). The solution is made with recycled paper with boric acid additives. Because of its composition, the solution is incinerated and not compostable.

The LCIA results with EF3.1 methodology highlight six hotspots for this manufactured material:

Table 33 Cellulose insulation LCIA, impact categories hotspots and results: 1 kg

Midpoint impact categories (EF3.1, hotspots 80%)	Unit	Value for 1kg	Contribution (%)	Hotspots, process contribution (80%)
Resource Use, minerals and metals	kg Sb eq	6,10E-05	49,22	Boric acid
Photochemical ozone formation	kg NMVOC eq	1,17E-02	9,34	EoL
Climate Change	kg CO_2 eq	4,19E-01	7,96	EoL > Electricity > Boric acid
Acidification	mol H^+ eq	8,97E-03	6,81	EoL
Ecotoxicity, freshwater	CTUe	2,46E+01	5,66	EoL
Eutrophication, terrestrial	mol N eq	3,93E-02	5,61	EoL
Resource Use, fossils	MJ	2,89E+00	2,52	Electricity > Boric acid > magnesium sulphate
Eutrophication, freshwater	kg P eq	3,11E-05	0,37	EoL > Electricity
Water Use	m^3 world eq	6,13E-02	0,31	Boric acid > Electricity
Land Use	dimensionless (pt)	8,38E-01	0,06	Boric acid > Electricity > EoL

From the table above and the figures below, the most contributing processes are:

- Boric acid
- EoL (see section IV.B.1)
- Electricity

Boric acid is an additive in the cellulose insulation. It is a mineral extracted from ore and mixed with strong acid. Because of this, it has a significant impact on the use of mineral and metal resources.

The electricity used to produce 1 kg of cellulose insulation influences impact categories such as Climate Change and Resource depletion, fossils.

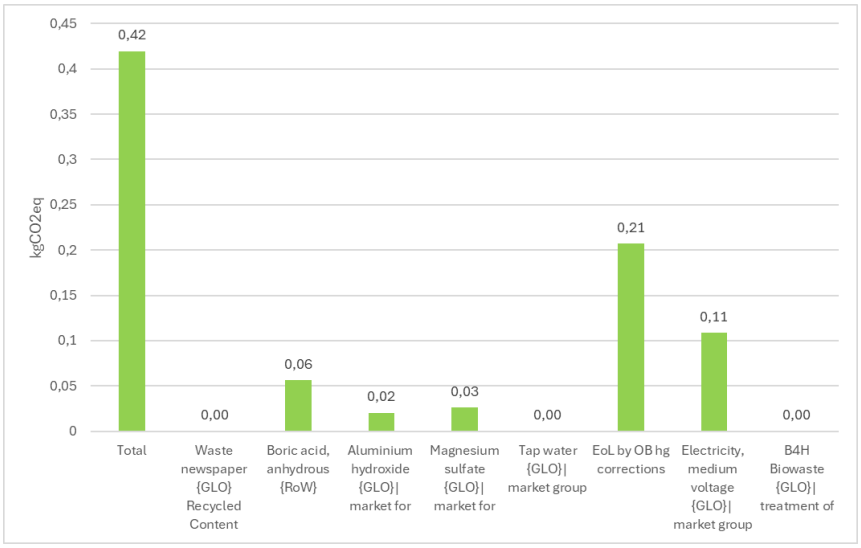


Figure 61 Cellulose insulation LCIA, Climate Change results: 1 kg

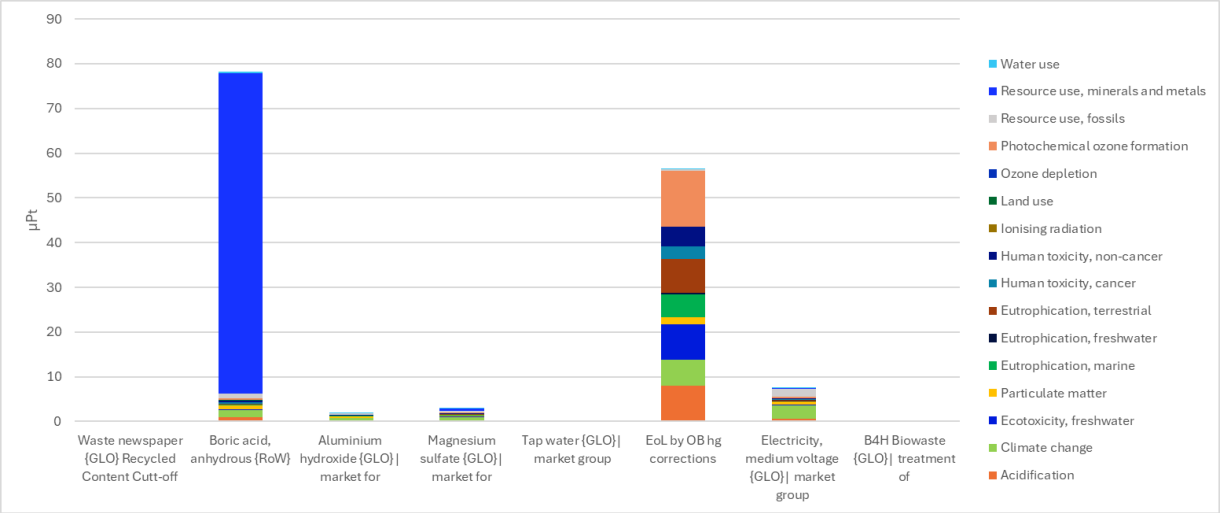


Figure 62 Cellulose insulation LCIA, single score results: 1 kg

h) Mycelium-based packaging

Mycelium-based packaging is used to protect fragile items during packaging as an alternative to polystyrene. It is made by growing fungal mycelium. A specific inventory was not made available, only the LCIA results of the solution provider are used in this study. The product is considered compostable and made from beech sawdust and wheat bran.

EoL is not included in the used LCIA, but respective impacts for EoL is supposed to be less significant as it is fully compostable (see IV.B.2.). The solution includes a small amount of nitrogen, potassium and phosphorus, which can have credits due to composting reaction that generates a fertiliser (no calculations available because no clear data). From the figures below, it is the production phase that contributes the most to the impacts, especially in terms of Climate Change. Both raw material and product productions have impacts on Water Use, Land Use and Eutrophication.

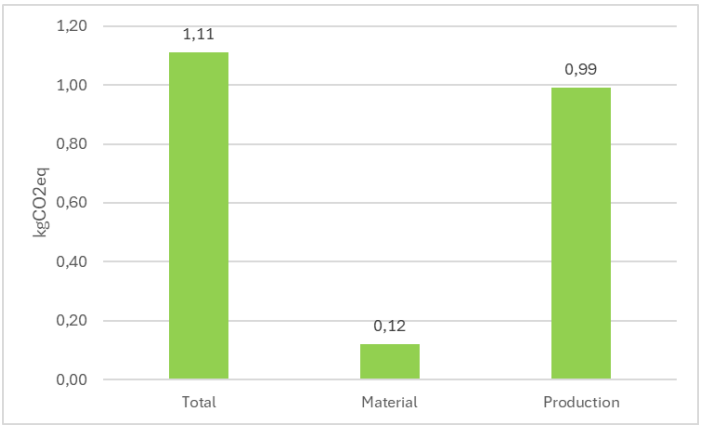


Figure 63 Mycelium-based packaging LCIA, Climate Change results: 1 kg

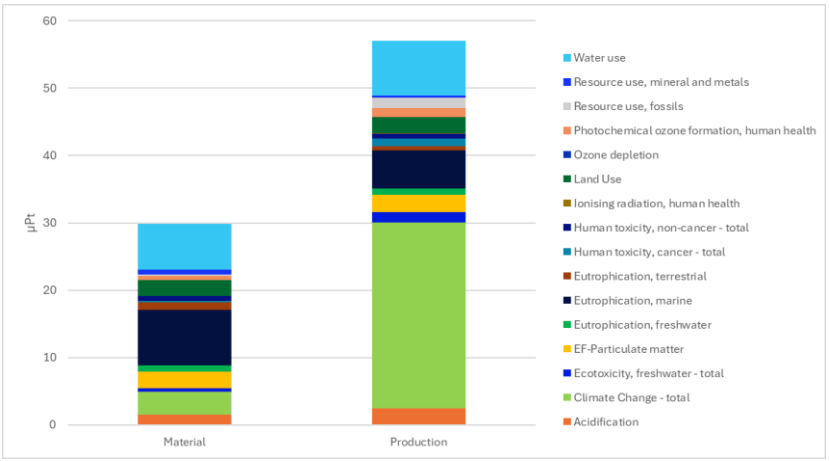


Figure 64 Mycelium-based packaging LCIA, single score results: 1 kg

i) Technologies solutions for EoL

To process biowaste in humanitarian aid settings, the Bio4HUMAN project revealed various solutions for biodegradable and biowaste products. These products can be composted, as suggested in previous sections, or put in digesters alongside biowaste. Here, five types of digesters will be studied for biowaste treatment: four anaerobic digesters (ADs) and one Black soldier Fly (BSF) bio-converter. These solutions offer interesting properties for waste valorisation in humanitarian settings, including biogas production or fertilising digestate production.

(1) Anaerobic digestion

In D5.1, an average of four types of biodigester solutions covering the solutions identified in WP4 was presented for biowaste (organic waste, from agricultural to food waste) anaerobic digestion (AD) including:

1. Modular renewable AD for high lignocellulose crops waste (e.g. straw, bagasse, wheat & rape), no additional energy because biowaste input is dry.
2. Single-stage digester for any biowaste, working in thermophilic conditions.
3. Micro-biogas digester for any sort of biowaste, working in mesophilic conditions.

4. Domestic digester for food waste or manure, thermophilic or mesophilic conditions.

The inventories of each specific technologies were not presented separately in D5.1 but are available in Annex VIII.B.3 of this deliverable. Credits for biogas are based on calorific values available in ecoinvent 3.10 and their credits are associated with the negative input of *Heat, central or small-scale, natural gas {GLO}| market group* for the EI3.10 dataset. Credits evaluation for digestate used as fertiliser (i.e. avoided impacts of purchasable fertilisers) and biogas production are detailed in VIII.B.3.

Figure 65 shows that the first option (modular micro digester for high lignocellulose crops waste) is the solution that has the lowest risks of impacts, based on EF3.1 methodology. It also shows that the single-stage, micro-biogas and domestic digesters are associated to higher impacts but comparable credits.

It is however important to highlight that the infrastructure is not included in the inventories. Indeed, Table 7 of D5.1 states that the four digesters are not composed of the same materials. For instance, the single stage AD (type 2) is built with locally sourced stones and cement, whereas the Micro-biogas AD (type 3) can be built with concrete or plastic. However, data on necessary quantity of the different materials is lacking and infrastructure impact is usually low, given the lifetime of the infrastructure. Therefore, depending on each digester's capacity for digestion and its structural materials, impact results might differ, but this aspect is not taken into account in the digesters analysis.

It can be concluded that the choice of AD does not significantly impact the benefits (credits) associated with biowaste digestion. So, any of these ADs are interesting to implement if the adapted biowaste are available.

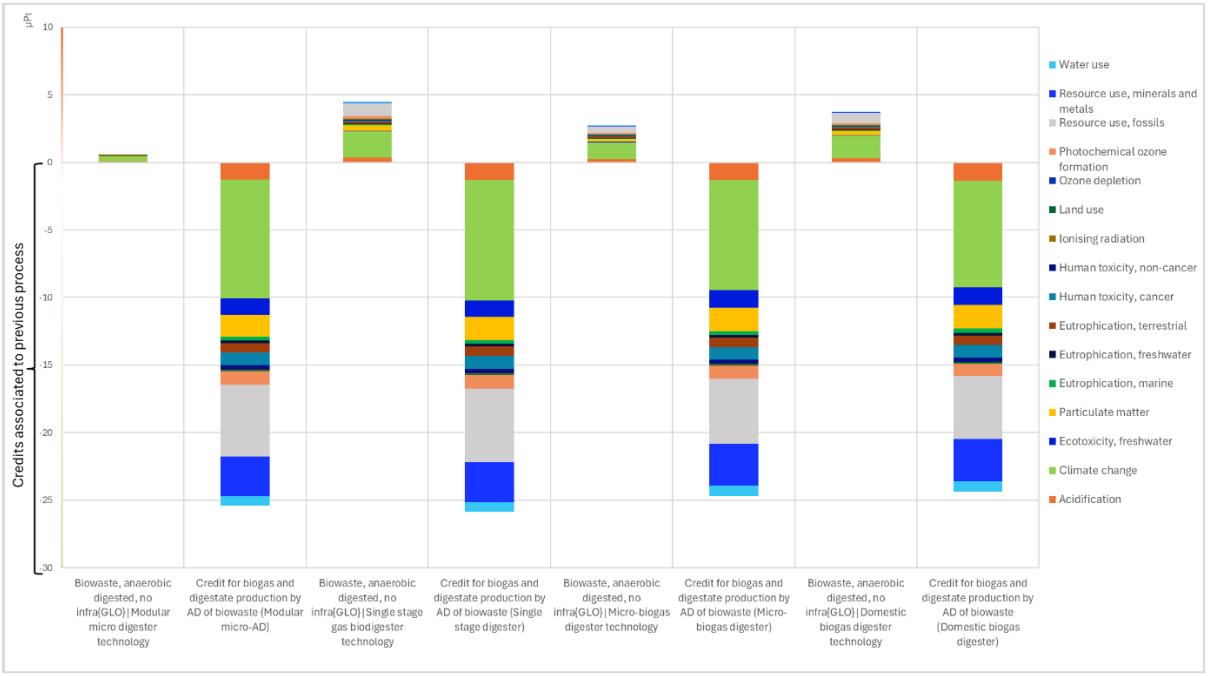


Figure 65 Anaerobic digesters impacts (EF3.1) and credits

When studying hotspots, the impacts of modular renewable micro-AD (1) are attributed to the home composting of the valorised digestate after AD (see Table 34, Figure 66 and Figure 67).

Table 34 Biowaste treatment in modular renewable micro-AD (1) LCIA, impact categories hotspots and results: 1 kg

Midpoint impact categories (EF3.1, hotspots 80%)	Unit	Value for 1kg	Contribution (%)	Hotspots, process contribution (80%)
Climate Change	kg CO_2 eq	1,29E-02	64,22	Digestate home compost
Acidification	mol H^+ eq	5,49E-05	10,92	Digestate home compost
Eutrophication, terrestrial	mol N eq	2,45E-04	9,17	Digestate home compost
Particulate matter	disease incidence	2,55E-10	6,83	Digestate home compost
Land Use	dimensionless (pt)	2,53E-01	4,38	Digestate home compost
Ecotoxicity, freshwater	CTUe	2,95E-03	0,18	Digestate home compost
Water Use	m^3 world eq	0,00E+00	0,00	_
Resource Use, fossils	MJ	0,00E+00	0,00	_
Eutrophication, freshwater	kg P eq	0,00E+00	0,00	_

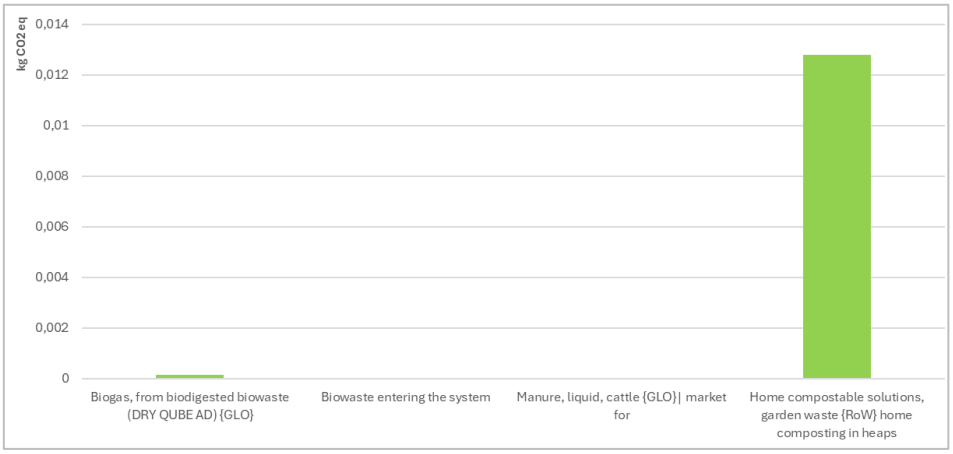


Figure 66 Biowaste treatment in modular micro-AD (1) LCIA, Climate Change results: 1 kg

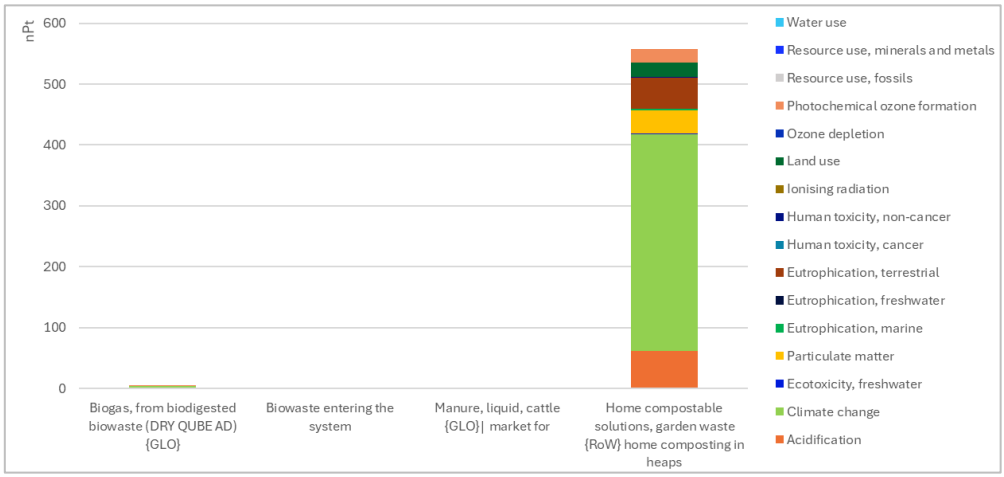


Figure 67 Biowaste treatment in AD LCIA, single score (EF3.1) results: 1 kg

On the contrary, the other three ADs (type 2, 3, and 4) that require energy inputs have higher impact risks, mainly due to electricity use. These three digesters present the same hotspots: they contribute to Climate Change, Resource Use, fossils, Particulate matter and Acidification as summarised in Table 35. As an example, the impacts of the Micro-biogas anaerobic digester (type 3) are displayed in Figure 68 and Figure 69.

Table 35 Biowaste treatment in Micro-biogas AD LCIA, impact categories hotspots and results: 1 kg

Midpoint impact categories (EF3.1, hotspots 80%)	Unit	Value for 1kg	Contribution (%)	Hotspots, process contribution (80%)
Climate Change	kg CO_2 Eq	1,51E-01	45,38	Electricity
Resource Use, fossils	MJ	1,76E+00	18,34	Electricity
Particulate matter	disease incidence	6,14E-09	8,69	Electricity
Acidification	mol H^+ eq	7,24E-04	8,44	Electricity
Eutrophication, terrestrial	mol N eq	1,61E-03	4,61	Electricity
Water Use	m^3 world eq	2,14E-02	4,31	Electricity
Ecotoxicity, freshwater	CTUe	3,48E-01	1,58	Electricity
Eutrophication, freshwater	kg P eq	3,48E-01	1,47	Electricity
Land Use	dimensionless (pt)	5,36E-01	1,29	Electricity

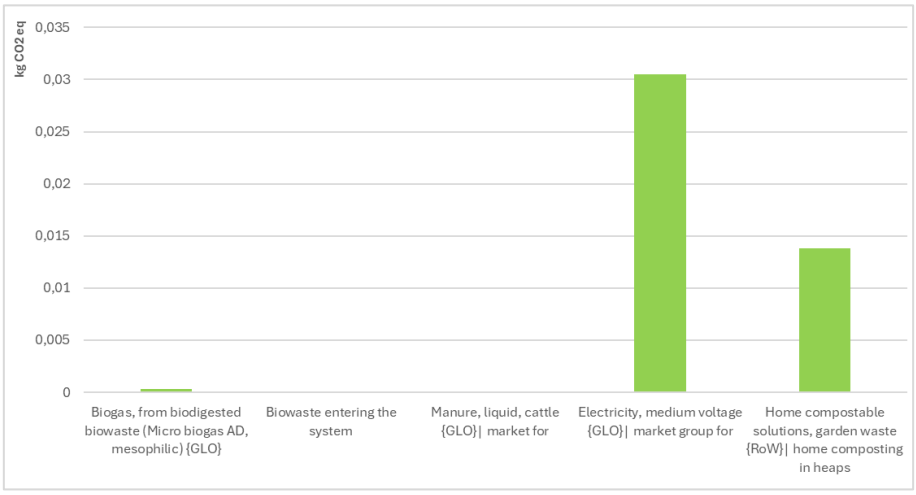


Figure 68 Biowaste treatment in Micro-biogas AD LCIA, Climate Change results: 1 kg

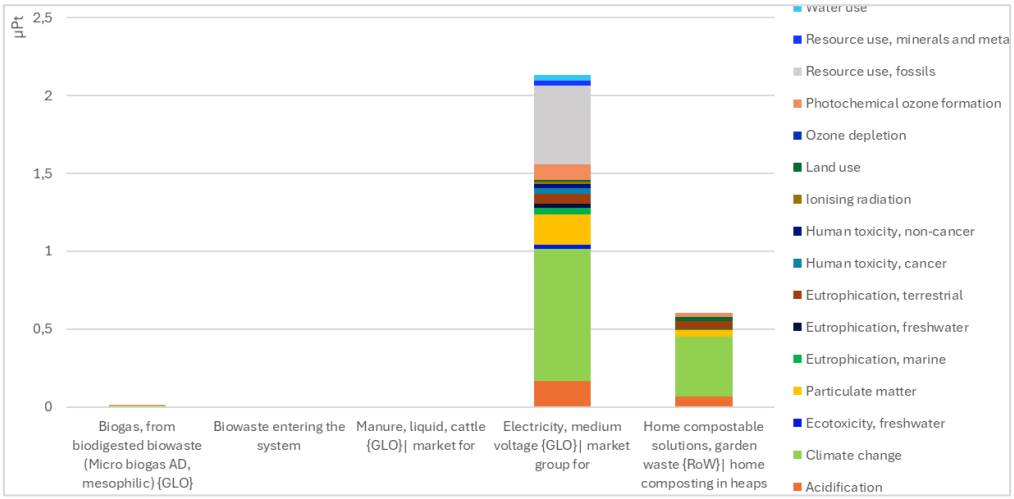


Figure 69 Biowaste treatment in Micro-biogas AD LCIA, single score (EF3.1) results: 1 kg

Given that electricity is a hotspot for AD impacts and that avoided heat has great impact on AD credits, the difference in energy mix in the DRC or SS could alter this analysis and the difference in impacts and credits will be assessed in Geographic availability assessment section VI.A.

In addition, it is interesting to study the benefits of producing biogas and obtaining a nutrient-rich digestate. These co-products avoid impacts associated with heat generation and fertilisers manufacturing. The digestate N, P, and K nutrient contents are presented in the Annex VIII.B.3.[44] The impacts of credits are presented in Figure 70. The results show that heat generation, as well as the fertilisers contained in the digestate, all present significant credits.

[44] Digestate liquid and solid content data from EI 3.10 "Biowaste {RoW}| treatment of biowaste by anaerobic digestion | Cut-off, U"

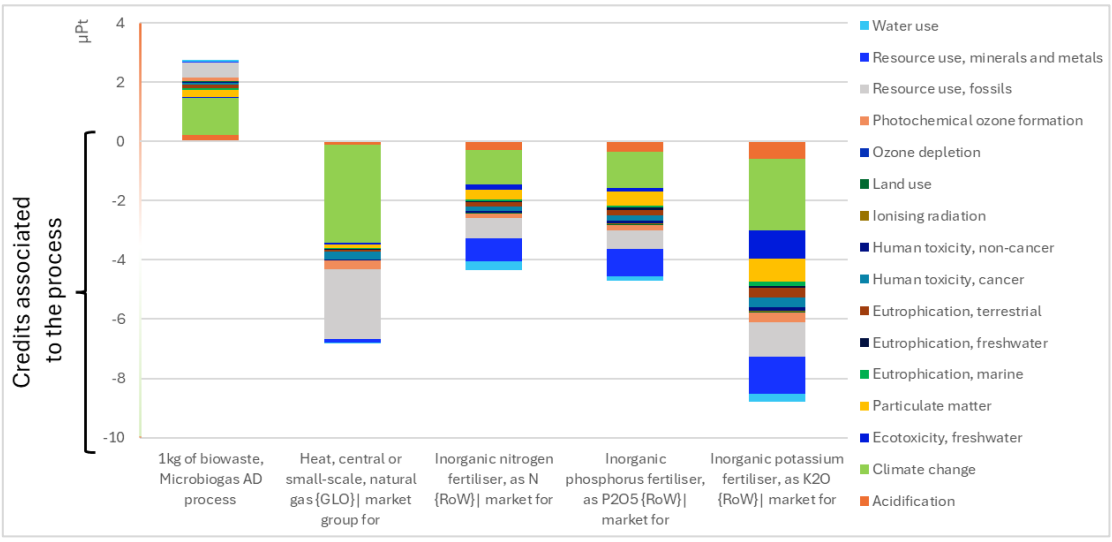


Figure 70 Biowaste treatment in Microbiogas AD LCIA and credits, Single score results: 1 kg

(2) Black Soldier Fly bioconversion

The impacts of biowaste conversion with Black Soldier Fly (BSF) on Climate Change are due to the use of electricity (see Figure 71). This electricity input is needed to mix the waste before digestion and to separate the products of the bioconversion. Both steps could be done manually. Also, electricity is used to oven-dry the produced larvae in the event natural drying is not an option. Therefore, electricity consumption is an important variable depending on the application the impacts could be lower.

However, Climate Change is not a hotspot category in this process. As can be observed in Figure 72, the hotspots (Acidification, Particulate matter, Eutrophication, terrestrial) associated with BSF are induced by direct emissions to air during bioconversion. Ammonia presents more than 90% the main impacts of direct emissions. This ammonia is emitted during the bioconversion process, but mainly during the post-composting of bioconversion residues. The output of the latter is a matured compost.

Table 36 Biowaste treatment in BSF bioconverter LCIA, impact categories hotspots and results: 1 kg

Midpoint impact categories (EF3.1, hotspots 80%)	Unit	Value for 1kg	Contribution (%)	Hotspots, process contribution (80%)
Acidification	mol H^+ eq	6,57E-03	30,13	Direct emissions to air
Particulate matter	disease incidence	4,61E-08	28,55	Direct emissions to air
Eutrophication, terrestrial	mol N eq	2,87E-02	24,76	Direct emissions to air
Climate Change	kg CO_2 eq	7,83E-02	8,98	Electricity > Direct emissions to air
Resource Use, fossils	MJ	6,63E-01	3,49	Electricity
Ecotoxicity, freshwater	CTUe	4,11E-01	0,57	Direct emissions to air
Water Use	m^3 world eq	8,05E-03	0,25	Electricity
Eutrophication, freshwater	kg P eq	2,47E-06	0,18	Electricity

Midpoint impact categories (EF3.1, hotspots 80%)	Unit	Value for 1kg	Contribution (%)	Hotspots, process contribution (80%)
Land Use	dimensionless (pt)	1,17E-01	0,05	Electricity

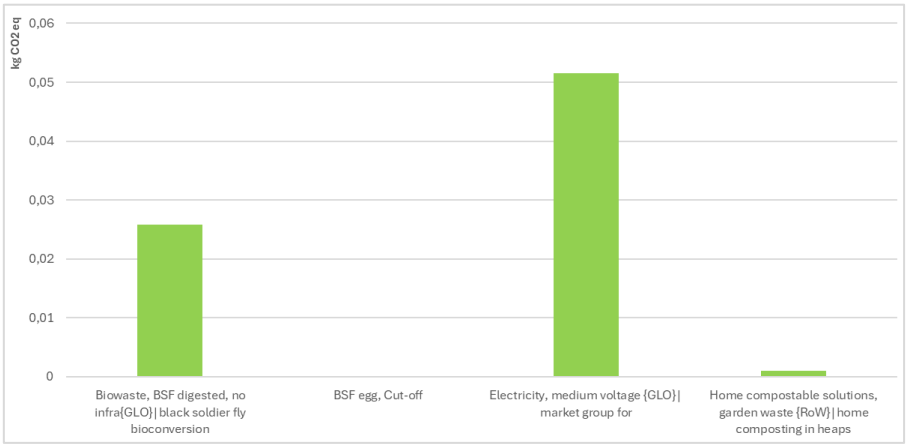


Figure 71 Biowaste treatment in BSF bioconverter LCIA, Climate Change results: 1 kg

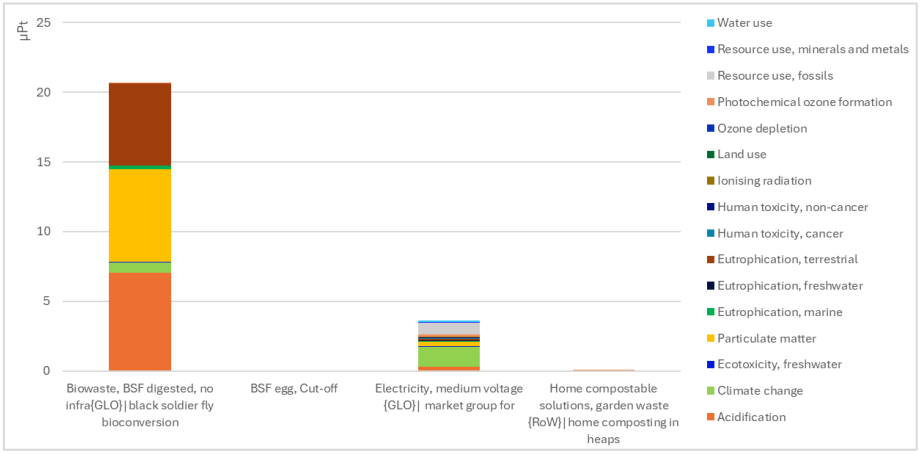


Figure 72 Biowaste treatment in BSF bioconverter LCIA, single score (EF3.1) results: 1 kg

The mature compost is also associated with fertilising credits, containing N, P, and K, mentioned in the reference article and summarised in Table 37.[45] The credits are presented in Figure 73. Compared to the biowaste conversion process, credits seem to be negligible.

Table 37 Credits associated to matured compost, obtained after biowaste BSF digestion

Fertilizing element	wt% of total solids of compost	Value for 1kg of biowaste treated: 0,651 kg of compost	Negative input process
N	1,274	-0,828 g	Inorganic nitrogen fertiliser, as N {RoW}| market for inorganic nitrogen fertiliser, as N | Cut-off, U
P2O5	1,08	-0,702 g	Inorganic phosphorus fertiliser, as P2O5 {RoW}| market for inorganic phosphorus fertiliser, as P2O5 | Cut-off, U

[45] Material flow analysis and life cycle assessment of food waste bioconversion by black soldier fly larvae (Hermetia illucens L.) - ScienceDirect

K2O	0,46	-0,299 g	Inorganic potassium fertiliser, as K2O {RoW}| market for inorganic potassium fertiliser, as K2O | Cut-off, U
Animal feed	**Quantity (for 1kg of biowaste treated)**		**Negative input process**
BSF-larvae	30.94 g		Soybean meal {RoW}| market for soybean meal | Cut-off, U

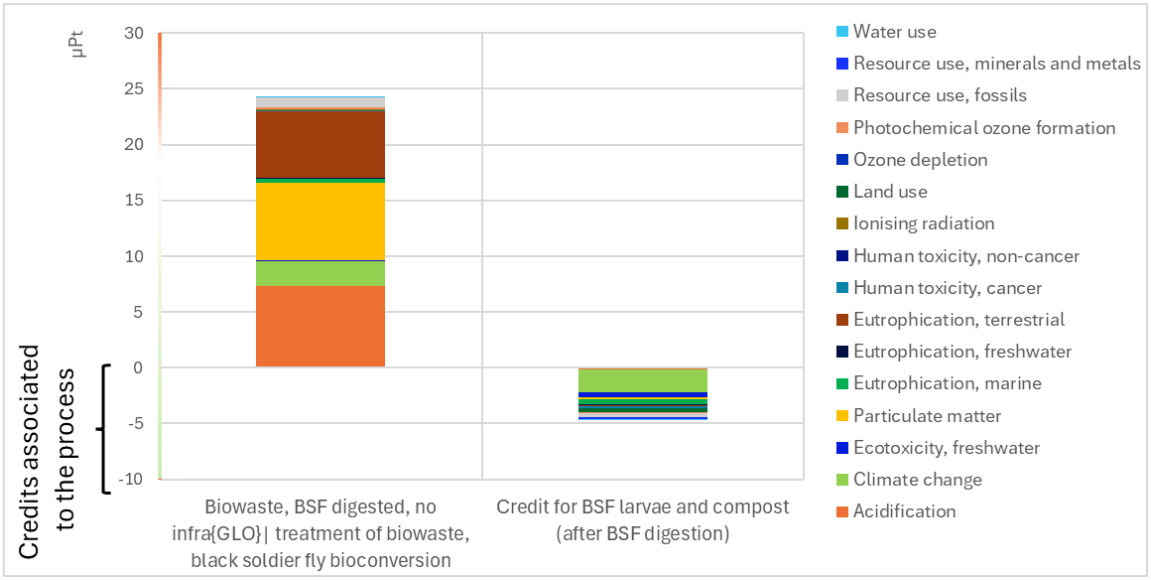


Figure 73 Biowaste treatment in BSF bioconverter with infrastructure excluded, LCIA and credits, Single score results: 1 kg

To conclude on the five identified EoL solutions, it is interesting to compare them to regular compost options (industrial and home composting). It is important to highlight that these conclusions do not take the infrastructure into account. Also, the composition of the waste can impact the emissions and the treatment efficiency. Therefore, even though one treatment technology may appear preferable with one type of biowaste, the results could differ with another. Anaerobic digestion appears here to be a viable solution with minimal impacts caused by digestion, resulting in biogas and digestate production, which may avoid the impacts of heat and fertiliser production.

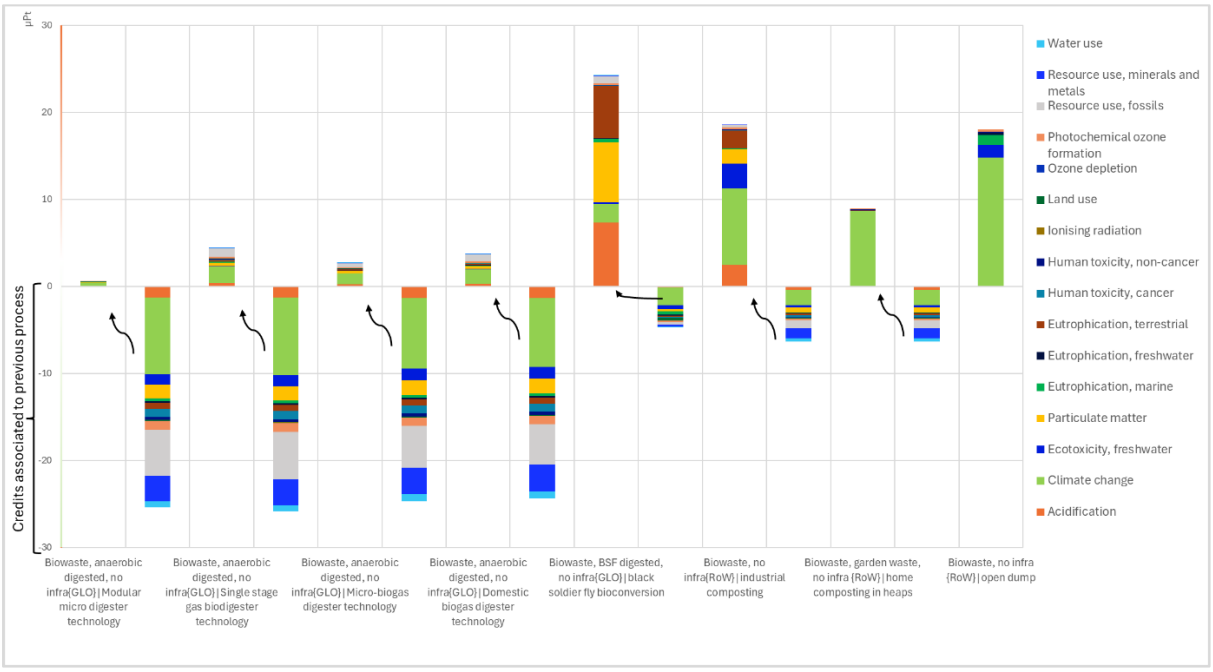


Figure 74 All Biowaste EoL treatment options analysis with infrastructure excluded, with credits, Single score results: 1 kg

j) Other indicators: solutions

To complete the hotspots analysis study, other indicators were studied: Plastic physical effect on biota (Impact World + methodology), Biogenic C uptake and emissions -1/+1 (EN15804+A2), and Material Durability Indicator.

Criticality of PLA and PE will also be assessed qualitatively, but in the section VI.A.

(1) Plastic's physical effect on biota

This indicator translates the effects of plastic on ecosystems into different categories of microplastics. Microplastics were associated with open dumping and unsanitary landfills (cf. reference EoL scenario) of unbiodegradable plastics, i.e. reference scenario items and packaging made of plastic.

All solutions here are either composted or open burnt, so there is no leakage of microplastics assumed.

However, it is worth noting that PLA is not always biodegradable, as it requires industrial composting. As film fragments microplastics, 1kg of PLA represents 7,8 PDF.m².yr, which is drastically inferior to HDPE film (481,3 PDF.m².yr). PLA high density leads to plastic sedimentation and limited impact on water. Its residence time is limited enough that the degradation rate into microplastics has no influence.

It is still important that PLA is handled correctly if introduced into HA packaging materials, even though it has less impact on water and biodiversity than HDPE. [46]

[46] https://linkinghub.elsevier.com/retrieve/pii/S0959652623023557 Bio-polylactic Acid (PLA) Market Analysis | Industry Growth, Size & Forecast Report

(2) Biogenic carbon uptake

As mentioned in IV.B.2, the degradation scheme for compostable solutions, consider biogenic CO_2, CH_4, and implies storing CO_2. Table 38 lists the carbon uptake and emissions at EoL, as well as the carbon storage after 100 years of degradation (if composted). Sheep wool has a significantly low degradation as explained in IV.A, and so 100% of the carbon content is considered to be stored in soil. Every solution that is open burnt emits the totality of its carbon content back into the atmosphere.

Table 38 Biogenic carbon uptake and emissions of bio-based materials, in kg CO_2,b, eq

Solution material (1kg)	Biogenic CO_2 equivalent absorption	**EoL process**	Biogenic CO_2 equivalent emissions after 100 years: CO_2,b eq= CO2,b+29.8*CH_4,b	Biogenic CO_2 equivalents after 100 years: (absorption)–(emissions)
	CO_2,b, eq (kg)		**CO_2,b eq (kg)**	**Carbon storage (kg)**
PLA bottle for oil and water	1,833	Industrial Compost	0,99	**0,75**
PHBV bottle for oil and water	2,196	Home Compost	1,19	**0.90**
Compostable sachet for RTUF	1,505	Home Compost	0,81	**0,61**
PLA + natural adhesive	2,275	Home Compost	1,23	**0,93**
Biodegradable laminating film	1,833	Industrial Compost	0,99	**0,75**
Mycelium protective material	1,200	Home Compost	0,65	**0,49**
Disposable bag from renewable sources	2,292	Industrial Compost	1,24	**0,94**
Foams for insulation	2,533	Open burning	2,53	**0,00**
Wool Insulation material	1,610	Home Compost	0.00	**1,61**
Bio-based insulation	1,598	Open burning	1,63	**0,00**
Cellulose-based insulation	1,628	Open burning	0,92	**0,00**
Organic disposable Sanitary pads with wings	1,703	Home Compost	0,99	**0,70**
Monofilaments Mosquito net	1,833	Industrial Compost	0,99	**0,75**

To conclude, using bio-based and biodegradable solutions also presents an opportunity to capture carbon at biomass production and integrate part of it into the soil at the EoL stage, through industrial or home composting.

(3) Ecosystem quality

This indicator aggregates environmental impacts into biodiversity damages (endpoint). Figure 75 displays how each material of each solutions affects biodiversity during their entire life cycle. 1kg of bio-based PUR foams for insulation has a significant impact, compared to other bio-based solution materials. It is important to note that the materials do not have comparable functionalities so they cannot be compared. This is also valid for building materials because 1kg of each

does not correspond to the same functionality (different thermal insulation capacities).

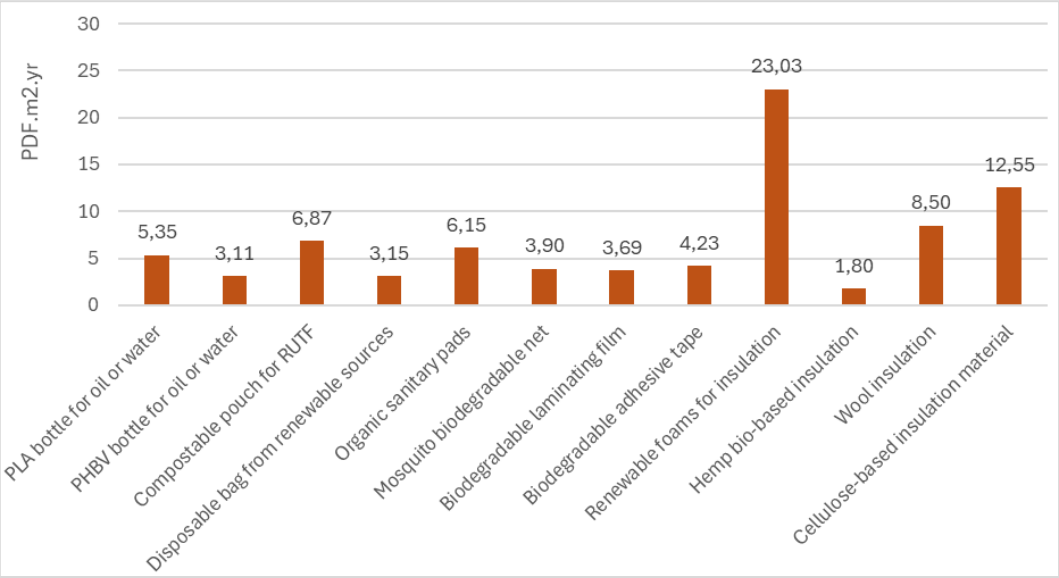


Figure 75 Solution materials impact on Ecosystem quality: Impact World+ v2.1: 1kg

(4) Material Durability Indicator MDI

With the eight indicators mentioned in III.B.3 retrieved from literature, an MDI of the reference material was calculated. Results are available in Table 39.

Table 39 Material Durability indicator of solution materials, building insulation excluded

Product material (1kg)	Oil and water bottle	Oil and water bottle	Pouch for RUTF	Adhesive tape	Biodeg. lam. film	Dispo. Bag from renewable resources	Organic sanitary pads	Mosquito net	Fragile items packaging
Base material considered	PLA	PHBV	Metallic cellulose	PLA	PLA	Bio-polyester	Cotton + bio-polyester	PLA	Mycelium
MDI	**39,9**	**14,6**	**1,3**	**42,7**	**45,7**	**29,1**	**Not applicable**	**45,6**	**No data**
Unit	No unit, between [1;400]								
References *(MR= mechanical resistance; ChR= chemical resistance)*	MR; Fatigue str.; UV resistance; ChR; Solvent resistance	MR; ChR; solubility	MR; ChR	MR; Fatigue str.; UV resistance; ChR; Solvent resistance	MR; Fatigue str.; UV resistance; ChR; Solvent resistance	MR; ChR	/	MR; Fatigue st.; UV r.; ChR; Solvent resistance	/

PLA- and PHBV-based material have a relatively low MDI because of important energy consumption and low flammability and solvents resistance, and their mechanical properties are rather low.

Pouch for RUTF, based on cellulose, has a low MDI due to its particularly low mechanical resistance, and lack of flammability and water resistance.

Lastly, the studied solution materials do not have particularly interesting durability properties, based on the MDI calculation methodology.

C. Interpretation

Plastic-based reference and solutions present **similar hotspots** over their life cycle (cradle-to-grave): *Climate Change, Resource Use, fossils, Particulate matter, Resource Use, minerals and metals, and Photochemical ozone formation*. Human Toxicity, cancer and Acidification occasionally come out as hotspots for some of the reference materials. As for the solution materials, other impact categories appear as hotspots: Water Use, freshwater Ecotoxicity and Acidification, driven by agriculture and EoL processes such as composting (both industrially and in garden heaps). The EoL of fossil-based plastics (reference scenario and plastics effect on biota) has a more significant impact on the LCIA results than the EoL of biobased and biodegradable solution materials through composting.

For **PLA**, it must be kept in mind that it is **not biodegradable** in the natural environment; it is only **industrially compostable** under controlled conditions. A study showed that out of five tested PLA samples, only four achieved complete biodegradation. With sub-optimal conditions, PLA has emitted microplastic fragments. Therefore, PLA materials must be collected thoroughly and appropriately treated to limit their impacts on biodiversity, even though it is preferable to polyethylene-based materials.[47] To limit food competition and environmental impacts, implementing **PLA recycling** could be an interesting solution to treat waste and limit the impacts associated to PLA consumption.

Furthermore, a pilot unit for PLA production from food waste has been tested by the University of Crete (Greece, 2022) and raised numerous challenges and concerns[48] to keep in mind when developing the PLA supply chain:

- Firstly, PLA is not biodegradable in the environment, so it does not tackle the issue of marine plastic pollution.
- Secondly, food waste was targeted as a very sensitive primary resource because it needs effective refrigeration throughout the supply chain to avoid premature fermentation of sugars (needed for lactic acid production, see Figure 32), development of pathogenic bacteria, or production of undesired ethanol, acetic acid, etc.
- Thirdly, food waste is not homogeneous, so PLA quality is variable, even if personnel are trained for sorting.
- Finally, PLA released a strong smell of “fish”, which can be disconcerting for beneficiaries.

Multi-materials, such as disposable pads and pouches for RUTF, present particularly **high impacts** due to their EoL by open burning. The emissions of particles associated with municipal solid waste by open burning are overestimated, but this process is a way of avoiding underestimation of EoL impacts due to open

[47] Bio-polylactic Acid (PLA) Market Analysis | Industry Growth, Size & Forecast Report
[48] https://www.uia-initiative.eu/en/pdf/2656

dumping, thanks to a viable EoL dataset in the ecoinvent database. As explained in IV.B.1, the latter does not take into account the plastic effects on biota resulting from leakage caused by open dumping. The multi-layer materials pose challenges at their EoL, because they cannot be easily sorted, and thus recycled, so waste management improvements in the HA regions would not significantly reduce the EoL impacts of these materials. Only **biodegradable alternatives can remedy EoL issues** if sufficiently available on the market. Bio-based polyester or PLA are emerging bio-sourced and biodegradable materials, and the potential supply criticality of PLA is studied in VI.D.

Based on the **MDI**, the reference materials and solution materials have **limited durability performance**, mostly due to low mechanical properties and low resistance to flammability. These results could have been expected, as they constitute packaging materials that do not require high mechanical resistance. However, **PLA**-based materials mechanical properties are **higher** than those of PE, which endows most solution materials with slightly greater durability indicators.

Building materials present various types of emissions at different life cycle stages. Glass wool impacts come directly from the raw materials, as glass is an energy-intensive material. Polyurethane foam impacts come from soybean and diisocyanate, as well as EoL. The impacts of cellulose-based materials are caused by open burning and the use of mineral additives. Hemp's direct emissions and the need for electricity pose most of the environmental impacts. Additionally, sheep wool comes from animals, so both direct emissions and food requirements are problematic.

The **solution materials are mostly composted at EoL**. In this section, other EoL solutions were studied for potential implementation in beneficiary countries. **Anaerobic digestion and BSF bio-converters** were identified in WP4, and the study concludes that AD impacts come from energy use, but BSF converter impacts come from direct emissions during post-composting. These waste treatments produce biogas and/or nutrient-rich digestate, which can offer supplementary products to beneficiaries and avoid the production of biogas or purchasable fertilisers.

To determine which materials and solutions are more interesting, **D5.3** will analyse the results using the **same functional unit** for the reference and the corresponding solution. This way, LCA will provide clear recommendations on how to select the most interesting solution and under which conditions. D5.2 consists of preliminary work to enable the comparison in D5.3 and the development of a decision matrix to assist HA organisations in making informed, sustainable decisions. Indeed, the results of environmental and social LCA, as well as LCC, will be aggregated in a single matrix to help choose the best materials for HA solid waste management.

The previous hotspot analysis has been conducted globally. However, environmental constraints can differ depending on the supply and beneficiary countries. In the following section, a geographic availability assessment will be conducted, focusing on grid mix, transportation sensitivity, and criticality of materials supply.

VI. Geographic availability assessment

A complementary geographic availability assessment allows us to consider the solutions' implementation in the two countries of interest: the DRC and SS. The outputs of this analysis will be used to help identify the best available innovative solutions for policymakers (T5.3).

A. Influence of grid mix

In solution materials and solutions for EoL, electricity and heat have been identified as a hotspot.

The grid mix and type of heat consumed in HA camps region could have significant impacts on the results for material production and EoL solutions, as identified in section V.B Materials hotspots analysis.

As presented in IV.C, energy production in the DRC and in SS are distinct from one to another. Figure 76 and Figure 77 display the difference between those two energy mixes. In the DRC, the impacts of electricity use are lower because 99,5% of the energy is hydraulic, whereas SS grid mix comes mostly from diesel. Regarding heat origin, the DRC produces heat mainly from biogas and in SS, mainly from oil.

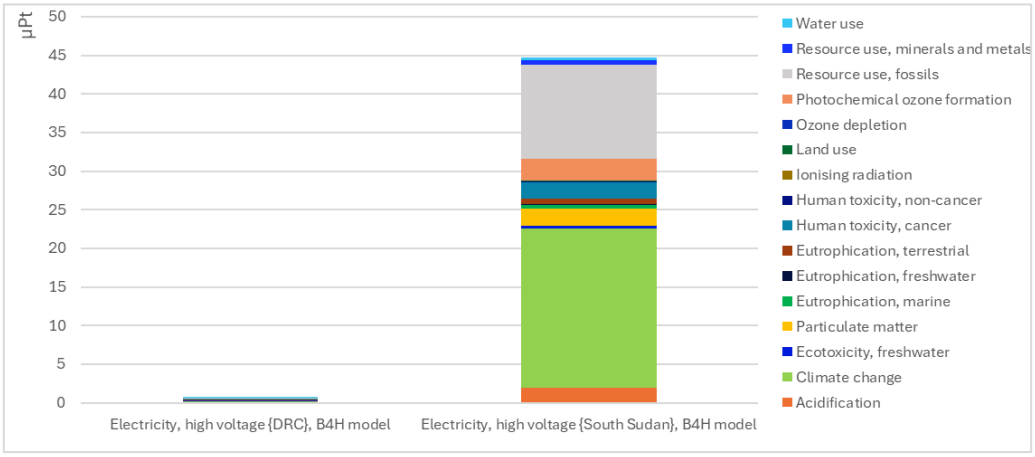


Figure 76 Electricity grid mix of DRC and SS: 1kWh, Single score (EF3.1)

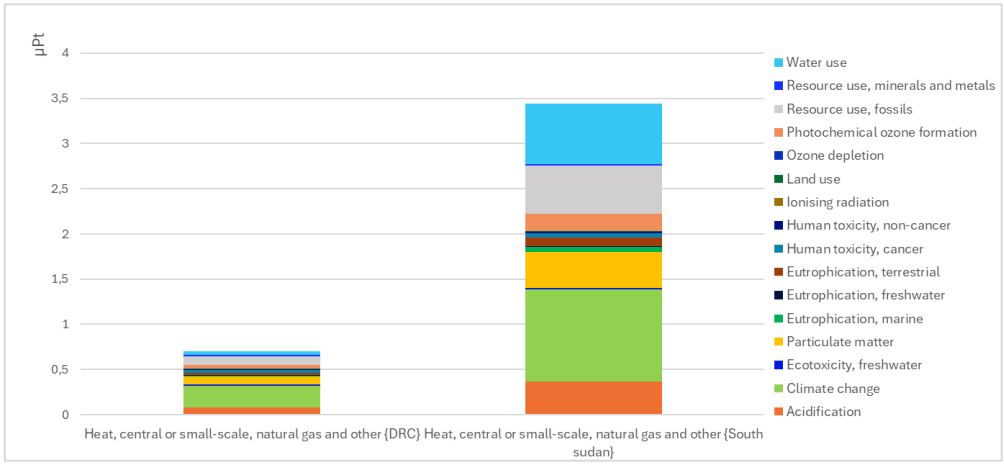


Figure 77 Heat production mix of DRC: 1 MJ, Single score (EF3.1)

Below, Table 40 summarises the impacts of each material if the grid mix is adapted (only the grid mix of the primary process and plastic manufacturing) to the HA regions: the DRC or SS. Values in red are superior to or equal to the global datasets impacts, so local production is not recommended. No transportation or use phase is included in the evaluated impacts, just as in the rest of this deliverable.

If local production were considered, please note that electricity availability nationwide (coverage[49]), national production capacity, and process complexity must be considered.

Table 40 Effects of heat and electricity mix on materials impacts: Single score and Climate Change

Solution material (1kg)	Impact assessment	Global market, impact	Production in DRC, impact	Production in SS, impact
PLA bottle for oil or water	Climate Change ($kgCO_2$, eq)	6,44	**4,51**	**6,30**
	Single score (mPt)	0,55	**0,42**	**0,53**
PHBV bottle for oil or water	Climate Change ($kgCO_2$, eq)	7,08	**5,16**	**6,93**
	Single score (mPt)	0,69	**0,56**	**0,67**
Compostable pouch for RUTF	Climate Change ($kgCO_2$, eq)	7,96	**7,96**	**8,03**
	Single score (mPt)	0,65	**0,65**	**0,66**
Disposable bag from renewable sources	Climate Change ($kgCO_2$, eq)	4,13	**3,37**	**4,15**
	Single score (mPt)	0,35	**0,29**	**0,34**
Organic sanitary pads	Climate Change ($kgCO_2$, eq)	1,66	**1,24**	**1,47**
	Single score (mPt)	0,42	**0,39**	**0,40**
Mosquito biodegradable net	Climate Change ($kgCO_2$, eq)	4,70	**4,18**	**4,73**
	Single score (mPt)	0,43	**0,39**	**0,42**
Biodegradable laminating film	Climate Change ($kgCO_2$, eq)	4,82	**4,24**	**4,77**
	Single score (mPt)	0,43	**0,39**	**0,43**
Biodegradable adhesive tape	Climate Change ($kgCO_2$, eq)	5,21	**4,36**	**5,93**
	Single score (mPt)	0,54	**0,48**	**0,57**
Renewable foams for insulation	Climate Change ($kgCO_2$, eq)	9,42	**9,16**	**9,42**
	Single score (mPt)	1,58	**1,56**	**1,58**
Hemp bio-based insulation	Climate Change ($kgCO_2$, eq)	1,13	**0,84**	**1,14**
	Single score (mPt)	0,11	**0,09**	**0,11**
Wool insulation	Climate Change ($kgCO_2$, eq)	7,30	**6,18**	**6,74**
	Single score (mPt)	0,96	**0,89**	**0,93**
Cellulose-based insulation	Climate Change ($kgCO_2$, eq)	0,42	**0,31**	**0,42**
	Single score (mPt)	0,15	**0,14**	**0,15**

B. End-of-life impacts: country grid mix and urban areas

The grid mix and type of heat consumed in the HA camps region could also have significant impacts on the results for EoL solutions, as identified in V.B.3.i). Therefore, a sensitivity analysis will underline the difference in potential impacts depending on local grid mix.

[49] Democratic Republic of the Congo - Countries & Regions - IEA; South Sudan - Countries & Regions - IEA

By using the **local grid mix or heat supply** (defined in IV.C and compared above), the impact of EoL solutions will vary. In this manner, the credits associated with EoL will also differ, because avoided impacts will not be the same. Figure 78 illustrates the sensitivity of the results depending on the regional grid mix. Anaerobic digestion seems most interesting in the context of the DRC, where electricity consumption is less impactful, but heat-avoided impacts are a less relevant than in SS. Indeed, heat from the DRC is also less impactful than in SS, so the avoided impacts are less significant. In any case, observations and conclusions made in V.B.3.i)(1) fostering AD as waste treatment stay valid in the DRC and in SS.

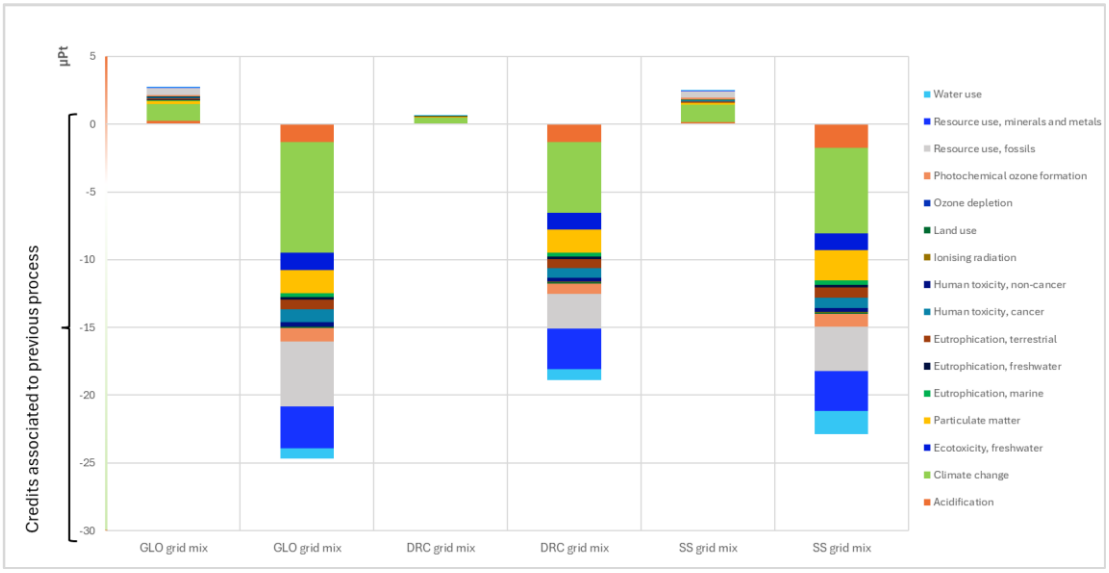


Figure 78 Grid mix Sensitivity analysis of anaerobic digesters impacts (EF3.1) and credits, example of Microbiogas AD.

However, it is particularly important to note that the modelling of the anaerobic digesters considered the digestate to be valorised with local composting. It does not take into consideration that, depending on the region, the requirements of N, P, or K are not equal, so avoided impacts would not be the same. Also, digestate composting is valid only in rural areas where effluent is valued as a fertilising agent for agricultural applications. Indeed, its transportation is a challenge due to its liquid form, thus it can only be used locally. Therefore, biogas producers in urban areas often discard the digestate back into the sewer system or directly into water bodies.

Additionally, only kitchen waste from households can be valorised as compost. Digestate coming from any unhygienic waste, such as human excreta, should not be used as a fertiliser. An additional step should be required, but this is not modelled in this deliverable. To evaluate the impact of digestate treatment in sewers instead of composting, a sensitivity analysis was conducted.[50] Figure 79 (Global geography) clearly outlines that, without valorisation by compost, waste treatment in sewers[51] adds significant impact to the process and the credits associated with fertilising are

[50] biowaste.pdf
[51] EI dataset: *Residues, MSWI, digester sludge {GLO}| treatment of residues, MSWI, digester sludge, residual material landfill | Cut-off, U*

set to zero. Credits due to biogas production alone are relatively low compared to the impacts of waste processing. If we compare this adjusted AD process for **unhygienic waste or urban areas**, Figure 80 shows that anaerobic digestion is then less relevant.

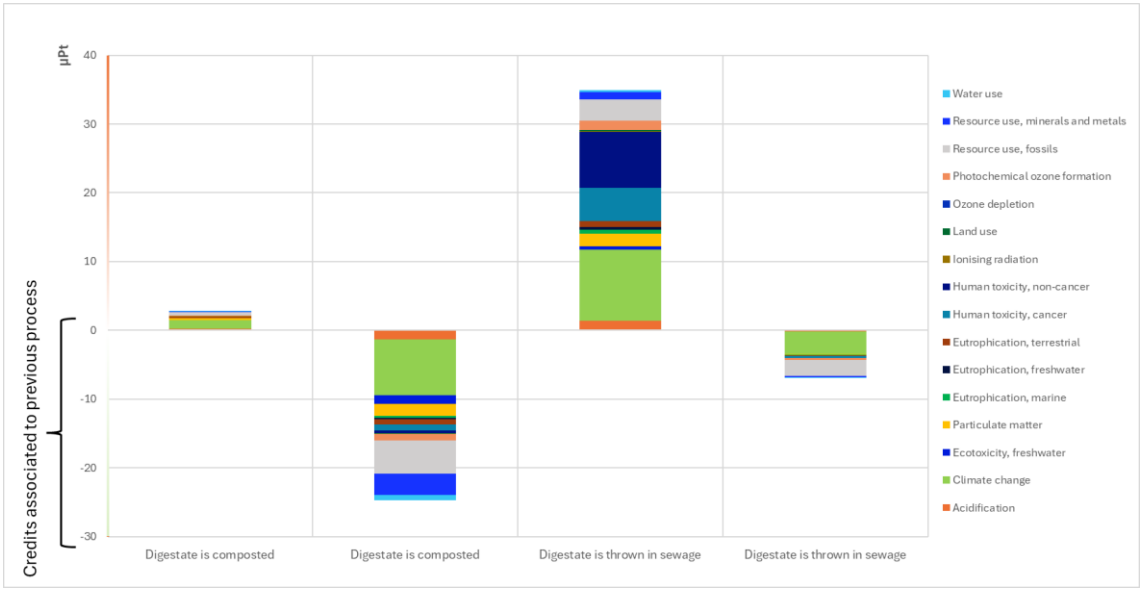


Figure 79 Digestate valorisation, Sensitivity analysis of anaerobic digesters impacts (EF3.1) and credits, example of Microbiogas AD.

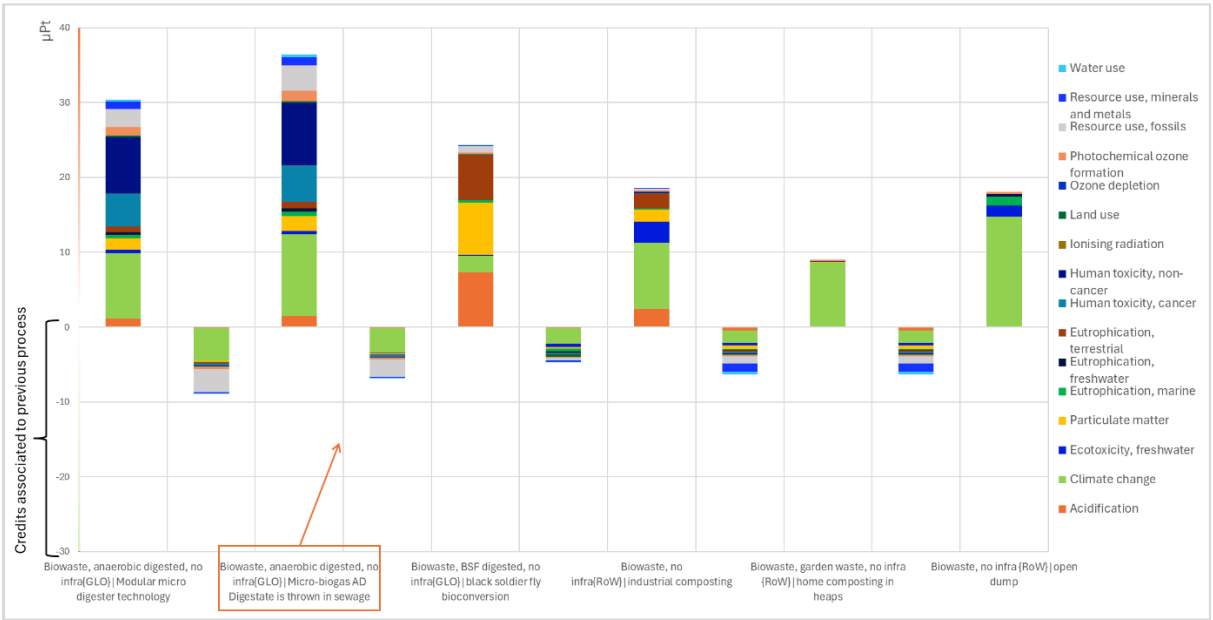


Figure 80 AD without digestate compost valorisation, Biowaste treatment options analysis, with credits, Single score results: 1 kg

To conclude, depending on the HA location and hence, waste treatment region, EoL solutions' impacts can vary, especially in the case of anaerobic digestion. **AD was proven most efficient in waste treatment** in V.B.3.i)(1), regardless of the grid mix. However, **in urban areas** where compost cannot be valorised, anaerobic digestion becomes **less interesting** compared to other waste treatment processes.

C. Transportation

In the DRC or in SS, 10% of the waste is collected (scenario elaborated in D3.3), and then, transported to the dumpsite. An average distance of 40km is considered in the DRC, based on the Mpasa household waste landfill[52] and of 14km in SS, based on Juba controlled dumping site[53].

Therefore, the environmental impact of the materials' EoL varies due to transportation at EoL. Collection of the waste occurs with a reference scenario, but also according to the solution material EoL.

In this deliverable, the collection distance was considered representative of both the DRC and SS (mean distance of 27.5 km). If we consider actual distances, the impact difference on EoL transport is 85% higher for SS compared to the DRC in Climate Change and Single score (EF3.1).

To put it into perspective, in the case of EoL of disposable bags from renewable sources, the industrial composting impact is +2.5% (Climate Change and single score) higher in SS than in the DRC, as shown in Figure 81.

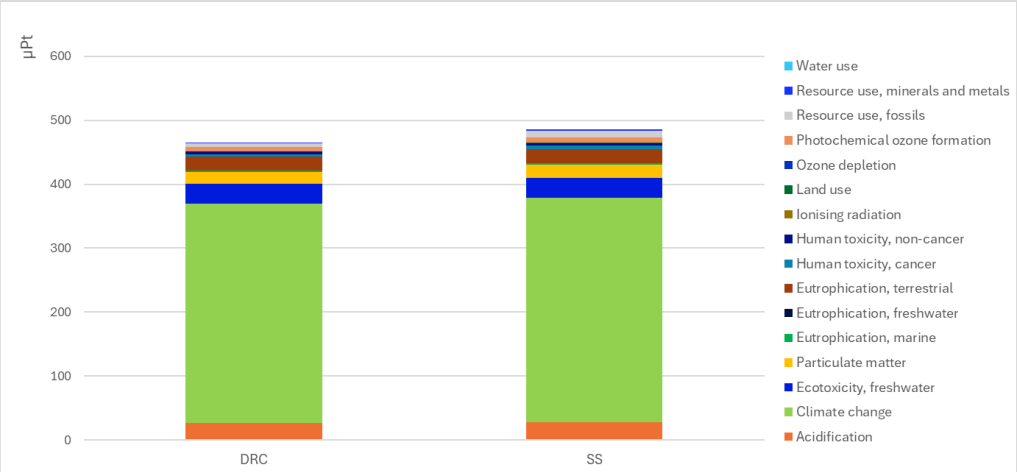


Figure 81 Sensitivity analysis on transportation for waste collection impact results on EoL impacts: example of industrial compost of disposable bags.

D. Criticality assessment

1. Introduction to criticality

The solution materials identified in Bio4HUMAN come from different supply chains than those of the reference scenario. It is interesting to focus on the criticality of the supply chain. Indeed, before being stored for HA, raw materials or components are distributed around the world. However, within the scope of HA, supply chains must be stable and reliable in case of emergencies.

A raw material criticality assessment method has already been developed for metals and technologies supply chains (International Round Table on Materials Criticality,

[52] Antea Group - Solid waste collection in Kinshasa, Democratic Republic of the Congo https://int.anteagroup.com/projects/solid-waste-collection-in-kinshasa#87043
[53] https://www.africancleancities.org/sites/default/files/2022/07/juba_en.pdf

IRTC method). It assesses the probability of a supply disruption of a raw material to a system and the vulnerability of this system to the latter disruption[54]. A raw material is "critical" if the production is monopolised by a specific region, for example. If this region presents political instability and is accompanied by other concerning factors such as high demand, high environmental and social impacts within the value chain, then the criticality is even higher[55].

Although no biotic materials currently figure on the list of raw materials catalogued as critical by the European Commission[56], a criticality assessment of bio-based solutions was found relevant in the scope of the CALIMERO EU project[57]. CALIMERO and other studies have pinpointed different dimensions of relevance to the bio-based sector criticality[58]:

- Environmental constraints (e.g. Climate Change, Acidification, Eutrophication, etc.).
- Social constraints (e.g. food security, compliance with environmental and social standards).
- Abiotic constraints (e.g. land availability and geopolitical tensions, water availability, natural disasters, etc.).
- Socioeconomic constraints (e.g. price fluctuations, concentration of resources and harvesting, demand increase, etc.).
- Physical constraints (e.g. resource depletion, replenishment rate, etc.).

The work performed in this section is inspired by the work within the scope of the CALIMERO, which also underlines the current limitations in the criticality assessment methodologies.

Due to the limited availability of data, the assessment conducted below for Bio4HUMAN is qualitative and presented in the form of a discussion, based on a comparative evaluation. Beforehand, the system, at risk of the study, as well as the goal of the assessment, will be defined in order to select the main criticality indicators of interest. This will define the framework for discussing indicator scoring and criticality assessment. Finally, mitigation measures will be provided, based on the observations made in this section.

2. System at risk

Here, the system at risk is HA, which relies on bio-based products to reduce solid waste scattering caused by HA activities. The goal of B4H is indeed to identify a list of bio-based solutions, but also to identify their sustainable performance, as well as potential drawbacks, such as supply chain gaps. Two countries of study were identified to focus the project on: the DRC and SS.

[54] Glöser S, Tercero Espinoza L, Gandenberger C, Faulstich M (2015) Raw material criticality in the context of classical risk assessment. https://doi.org/10.1016/j.resourpol.2014.12.003
[55] Schrijvers D, Hool A, Blengini GA, et al. (2020) A review of methods and data to determine raw material criticality. https://doi.org/10.1016/j.resconrec.2019.104617
[56] European Commission (2023) Study on the Critical Raw Materials for the EU 2023 - Final report
[57] Calimero D3.3. Circular economy and criticality assessment methodology definition (2024)
[58] Bach V, Berger M, Finogenova N, Finkbeiner M (2017) Assessing the availability of terrestrial Biotic Materials in Product Systems (BIRD). https://doi.org/10.3390/su9010137

The identified solutions primarily rely on bio-based plastics, such as PLA. To represent the bio-based identified solutions, it has been decided to focus this criticality assessment on the procurement of PLA products to the DRC and SS. Accessibility to PLA will be studied by focusing on raw materials (sugarcane, maize or biowastes) as well as the PLA production step. The distribution of the PLA products will also be studied by assessing the DRC and SS constraints.

3. Objective of the assessment

The goal of this criticality assessment is to determine if the production of bio-based materials for packaging is stable and reliable for HA. In parallel, this criticality assessment will potentially help identify whether it enhances water and food procurement issues in supply countries. These issues have been identified as of major concern to the HA organisations of the Bio4HUMAN consortium. Indeed, it is important that changing the material supply does not endanger populations in other regions.

Accessibility to PLA and its associated risks will be studied by focusing on accessibility to raw materials (maize or sugarcane) or biowastes, as well as the PLA production step. The distribution step will also be studied by assessing the DRC and SS country performance. Based on the market share on raw materials for PLA production and PLA production itself, the goal is to determine if one type of resource (maize, sugarcane, or biowaste) presents a higher risk of supply disruption than the other. To put it into context, the results will be compared to those of a typical fossil-based plastic, widely used in the reference scenario: polyethylene (PE).

4. Selection of the indicators

As there is no standardised way to perform a criticality assessment of bio-based products, it was decided to focus the criticality assessment study on the following indicators, amongst those listed by Schrijvers et al. (2020)[59] and in the CALIMERO Excel tool:

- **Concentration of supply** will underline procurement risks due to dependency on specific suppliers. If the number of suppliers is lower, the risk is higher.
- **Water Depletion Index** will depict how the biotic materials compete with the local water supply to the population. It will be analysed alongside Water Use LCIA results (EF3.1).
- **Food Security Index** will depict how the biotic materials compete with the local food supply to the population.
- **Economic Vulnerability Index** portrays how the land structure and the region's exporting strategies impact the vulnerability of the region. It aggregates economic and environmental shock indicators.
- **Worldwide Governance Indicator** reflects how the country is governed and its policies' stability.
- **Biotic resource depletion** reflects the interaction between the extraction rate, the resource stocks and the replenishment rate of the biotic materials.

[59] Schrijvers D, Hool A, Blengini GA, et al. (2020) A review of methods and data to determine raw material criticality. https://doi.org/10.1016/j.resconrec.2019.104617

- **Land Use** underlines problems related to land use and transformation. This indicator is taken from EF3.1.
- **Cumulative energy demand** (version 1.12 of the eponymous methodology) underlines dependency on energy price fluctuations.

These indicators come from IRTC (criticality method, initially developed for minerals and metals) and the BIRD methodology, developed for the bio-based sector. They were selected as they best represent the issues related to the use of bio-based products for HA, described in section VI.D.3.

However, in the case of maize and sugarcane, biotic resource depletion has less importance in the assessment because both crops are grown across the world and grow annually. This indicator does not consider biowaste; thus, this indicator will not be integrated into this study. However, it could be interesting to take it into consideration if other biotic resources should be considered in future works.

5. Data availability and quality

a) Market shares

To perform this assessment, a market share state-of-the-art assessment was conducted to provide data on biotic raw materials procurement: maize, sugarcane, and biowaste. The same has also been done for the PLA production step and for PE production.

Sugarcane and maize market data were extracted from the OECD database[60]. Market share was defined based on production volumes of countries that produced more than 100 kt of crops per year and for which production represented more than 1% of global production. See the collected data in Table 41 and Table 42.

Table 41 Raw materials origin: Market share of maize production, considered for criticality assessment

Producing Country	Canada	USA	Russia	Ukraine	Spain≈ E.U. [61]	Argentina
Production share (%)	1,1	27,2	0,9	1,8	4,7	3,6

Producing Country	Brazil	Mexico	China	India	Indonesia
Production share (%)	8,6	1,96	21,16	21,16	2,74

Table 42 Raw materials origin: Market share of sugarcane production, considered for criticality assessment

Producing Country	USA	Australia	South Africa	Argentina	Brazil	Colombia
Production share	1,8%	1,8%	1,1%	1,2%	41,1%	2,3%

[60] OECD Data Explorer • OECD-FAO Agricultural Outlook 2025-2034
[61] Spain was considered as a country representing an average situation in European Union, between most developed and less developed countries, because European granularity of data was not available.

Producing Country	Mexico	China	India	Indonesia	Pakistan	Philippines	Thailand
Production share	3,3%	6,32%	22,90%	2,08%	5,55%	1,34%	5,92%

PLA from biowaste represents a small portion of PLA production[62]. When that is the case, biowaste is sourced locally to avoid biowaste transportation, which would override the cost and environmental benefits.[63, 64]

For PLA material market share, studies conducted in 2022 allowed a compilation of a representative market share of PLA production. Indeed, even though a lot of companies for PLA are European, the majority of PLA is processed in the USA, Thailand, China and other Asian countries. For this study, it was essential to consider the producing country and not the headquarters.[65, 66] Also, it is important to note that production from the USA is dominated by NatureWorks, manufacturing only from maize grain, and production in Thailand is dominated by Total Corbion, which relies on sugarcane. Hence, the difference in PLA from maize and PLA from sugarcane market shares is shown in the *following tables*. Data on raw materials of other producing countries was not found and considered in both cases. This assumption could be refined in future works.

Table 43 Processing countries origin: Market share of PLA from maize production, considered for criticality

Producing Country	USA	China	Japan	Netherlands
Production share	24%	74%	1,60%	0,80%

Table 44 Processing countries origin: Market share of PLA from sugarcane production, considered for criticality

Producing Country	Thailand	China	Japan	Netherlands
Production share	13%	85%	1,67%	0,83%

As biowaste is collected locally, the market shares were defined under two theoretical scenarios:

a) Biowaste comes from the DRC or SS (100% of market share) for a local PLA industry implementation.
b) 0r, biowaste comes from the PLA manufacturing countries, and the proportions for biowaste market share are equal to PLA market share (maize- and sugarcane-based). See Table 45.

Table 45 Processing countries origin: Market share of PLA from biowaste production, considered for criticality

Producing Country	USA	Thailand	China	Japan	Netherlands
Production share (scenario b)	21,0%	10,0%	67,0%	1,7%	0,8%

[62] A review on biodegradable polylactic acid (PLA) production from fermentative food waste - Its applications and degradation - ScienceDirect
[63] Bioenergy Project Development and Biomass Supply - Good Practice Guidelines
[64] https://www.uia-initiative.eu/en/pdf/2656
[65] https://prismaneconsulting.com/report-details/polylactic-acid-pla-market-analysis-and-forecast-report-2032
[66] https://prismaneconsulting.com/blog-details/biodegradable-plastics-capacity-additions

PE market share data was not available country by country, so the data did not match the country granularity necessary for the CALIMERO Excel tool. The study of Plastics Europe was used as a base for the polyethylene market share[67]. It was considered that the fossil-based plastics share followed PE production and polypropylene (PP), the two most produced plastic materials globally. Granularity was available for European countries but not for the rest of the world. A PE growth report showed that in the Asia Pacific (excluding China and Japan), Thailand, Vietnam, and Indonesia were also important Asian PE producers, followed by India, Japan and finally Myanmar, Cambodia, and the Philippines.[68] India's market share was defined based on a market size and outlook study[69], and Japan's share was retrieved from the Plastics Europe report. Thailand, Vietnam, and Indonesia were arbitrarily allocated 85% of the remaining Asian Pacific percentages (4,2% each), whereas Myanmar, Cambodia, and the Philippines were allocated the remaining 15% (0,99% each). In the end, table below represents the considered market share for PE production in this study:

Table 46 Market share of PE, considered for criticality

Producing Country	USA	Netherlands	China	India	Saudi Arabia	Japan	Thailand
Production share	17,1%	1,3%	33,3%	4,2%	8,5%	2,8%	4,2%

Producing Country	Vietnam	Indonesia	Spain ≈ rest of EU	Germany	Belgium	France
Production share	4,2%	4,2%	2,78%	2,55%	1,81%	1,38%

b) Selected indicators

Concentration of supply depends on the number of countries identified in the market share. Precision depends on raw material market share data (see VI.D.5.a)). It is calculated by the Herfindahl–Hirschman Index (HHI), based on the number of producing countries and their contribution (in %) to the annual production (Available in the CALIMERO Excel tool).

Water Depletion Index data dates back to 2018 and is country dependent.[70] It is also available in the CALIMERO Excel tool. It will be analysed alongside Water Use LCIA results (EF3.1);

Food Security Index data dates back to 2018 and is country-dependent (Available in the CALIMERO Excel tool).

Economic Vulnerability Index is retrieved from the UN CDP study of 2024[71] (Available in the CALIMERO Excel tool).

[67] Plastics – the fast Facts 2024 • Plastics Europe
[68] Polyethylene Market Size & Share, Growth Report 2035
[69] India Bio-based Polyethylene Market Size & Outlook, 2030
[70] WAVE - TU Berlin, Calimero excel tool
[71] Publications | Economic Analysis and Policy Division, Calimero excel tool

Worldwide Governance Indicator data comes from World Bank reports of 2022, based on the year 2020 (Available in the CALIMERO Excel tool).

Land Use is taken from EF3.1. LCIA results of the LCA analysis conducted above. Other environmental indicators of EF3.1. will also be partly studied due to their potential impact on criticality: Climate Change, Acidification, marine, freshwater or terrestrial Eutrophication. These were obtained from the inventories for PLA obtained in V. Life cycle impact assessment. For PE, ecoinvent v3.10 dataset Polyethylene, high density, granulate {RoW}| polyethylene production, high density, granulate | Cut-off, U was used.

Cumulative energy demand is calculated based on PLA production inventories with the Cumulative energy demand methodology, on SimaPro with ecoinvent database.

6. Indicator scoring using the CALIMERO Excel tool

Criticality results focused on selected indicators (VI.D.4) on two life cycle stages: raw materials production (crops and biowaste), and plastic production (PE and PLA). The tool has a database of economic and geopolitical indicators for potential supply countries. When entering market shares of raw materials and plastic production, the tool normalises (the highest value corresponds to 100%, the higher the worse), aggregates, and weights (by country share input) each indicator, providing relative quantitative results. With this methodology, the material criticality can be assessed with a comparative analysis.

The distribution step will be assessed based on country performance data only (the DRC and SS). The data will be compared to the performance of raw materials. A difficult distribution can induce criticality, even if the supply is reliable.

7. Results and interpretation

Figure 82 shows that **Concentration of supply** is **most problematic** for PLA based on **biowaste** in the DRC or SS. Indeed, as mentioned above, biowaste can only be sourced locally. Therefore, in the case of a local production in SS and the DRC, biowaste sourcing is limited to these countries. In the case of a global market, 98% of biowaste is sourced from the main producers of PLA, i.e. China, the USA and Thailand, making the sourcing opportunity is more diverse. For crop-based PLA, the supply concentration differs depending on the feedstock. In the case of sugarcane-based PLA, production is more geographically concentrated, with Brazil and India accounting for around 65% of global sugarcane output. In contrast, maize, the primary feedstock for PLA, is more evenly distributed, with the USA, China, and India together producing approximately 70% of global maize, in relatively equal shares. Also, to manufacture PLA itself, China holds about 85% of the market with sugarcane, whereas with maize-based PLA, China is considered to hold 74%. Ultimately, the concentration of supply is problematic at the raw material sourcing stage and at the PLA production stage.

Food Security Index reveals significant issues regarding food stability in the DRC (see Figure 82). This is probably similar for SS, but the CALIMERO tool database did

not have data for this country-specific performance indicator. Nevertheless, PLA is considered to be synthesised from biowaste here, so the issue is directly addressed. It confirms, however, that PLA production from crops in this country would endanger further the food security in the DRC and possibly SS. In addition to this analysis, it can also be stipulated that the countries involved in PLA production from sugarcane (i.e. Thailand) present higher risks than those for maize-base (i.e. USA).

Regarding **Economic Vulnerability Index (EVI),** economic and environmental shock indicators are worse for SS and the DRC-based production than for the regions involved in PLA production from maize and sugarcane (see Figure 82). In this case, sugarcane-based production seems, however, to be more sensitive than the maize-based. It is also worth noting that PE procurement presents less EVI risks than any other type of PLA.

Worldwide Governance Indicator (WGI) depicts the highest governance instability for production in the DRC and SS in Figure 82 (theoretical situation, based on biowaste resource). Similar to the EVI indicators, sugarcane-based PLA production presents higher risks than maize-based, and PE procurement presents less risk than any type of PLA due to governance issues.

Water Depletion Index (WDI) reveals the most important water competition in the case of polyethylene supply countries. However, the **Water Use** of EF3.1 methodology adds additional information about the consumption of the actual production process (see Figure 82). By analysing both indicators, one can see that PLA from maize presents the highest risks, followed by PLA from sugarcane, and PE. Water Use in the case of biowaste-based PLA in SS is high due to heat generation from oil, which is associated with high water consumption. This heat is necessary for the synthesis of PLA from biowaste. Although the WDI is low in SS, this issue should still be addressed.

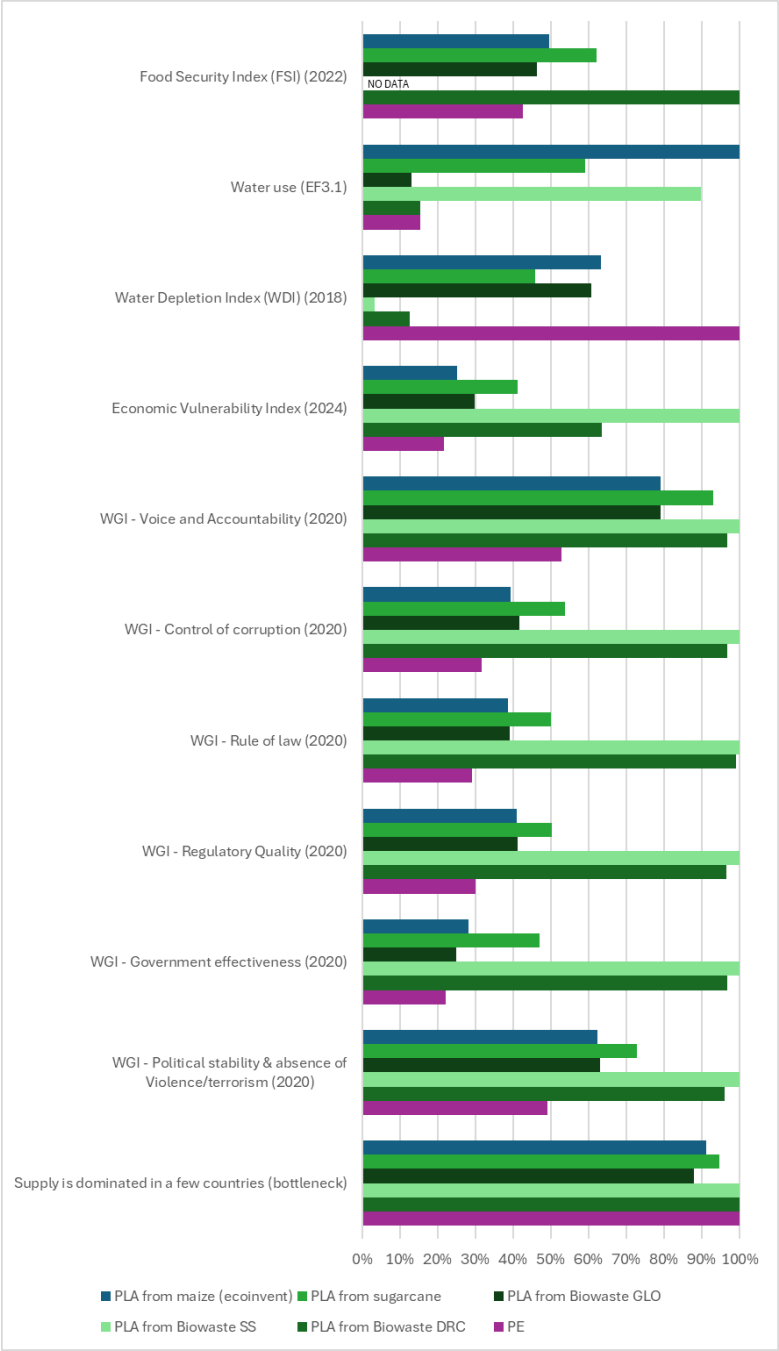


Figure 82 Supply countries indicators for criticality assessment (the higher, the worse)

Whereas Figure 82 shows a selection of country-specific indicators, Figure 83 focuses more on material-specific indicators.

Land Use issue is prevalent in the case of PLA from sugarcane and maize. When studying the causality with LCIA results, it shows that maize land use is superior to that of sugarcane (source: ecoinvent), but a higher score for PLA from sugarcane is due to the difference in production yields. Indeed, with yields retrieved from V.B.3.a) of 65% and 2.2% (+5.26% for ethanol), respectively, maize is less impactful on Land Use. Therefore, other environmental impact indicators related to criticality problems also show higher risks due to PLA production from sugarcane, except regarding

freshwater Ecotoxicity and Climate Change. For more information on environmental impacts, please refer to V.B.3.a) PLA production impact assessment and analysis.

Although biowaste limits land use, it is important to underline that biowaste can be considered as a **by-product**. It means that its production is dependent on another activity like agriculture, overproduction, cooking, etc. Biowaste supply is local and dependent on biowaste production in each PLA-synthesising country. Indeed, biowaste supply is complex in the goal of PLA synthesis because waste must be properly refrigerated during transportation to avoid premature fermentation[72]. Thus, biowaste must be sourced locally and it can be supposed that a country like China, second in biogas production after Germany, already has a reliable biowaste supply chain. [73] Additionally, countries with large populations and higher levels of development may tend to generate more food waste, but the risk of intentionally producing waste for PLA production is to be avoided.

In the event of the disruption of food waste production due to food management improvements or famines, there might be a **shortage** in biowaste procurement as well as price fluctuations. As highlighted by the United Nations Sustainable Development Goal 2, food waste presents ethical concerns. For instance, food waste value should be limited to avoid selling undesirables to PLA producers instead of local food banks, for instance. Indeed, even though enough food is produced globally to meet every person's needs, a third of the world's population suffers from food insecurity[74]. Therefore, **biowaste cannot be considered a unique biotic material for PLA synthesis for logistical and ethical reasons**. Furthermore, food insecurity is high in the DRC and SS, so food waste should be as low as possible. Hence, producing PLA in the DRC and SS from biowaste or even from edible crops can be problematic. In the end, developed countries (global scenario) that already produce PLA from crops would be more interesting to develop PLA production from biowaste supply chains.

Finally, **Cumulative energy demand** results imply that sugarcane-based PLA is the most energy-reliant process. Therefore, its price presents risk of fluctuation due to the evolution of energy prices. To avoid that problem, maize-based PLA emerges as the best solution, even better than polyethylene.

[72] https://www.uia-initiative.eu/en/pdf/2656
[73] State of the biogas industry in 12 member countries of IEA Bioenergy Task 37 – Bioenergy
[74] Goal 2 | Department of Economic and Social Affairs

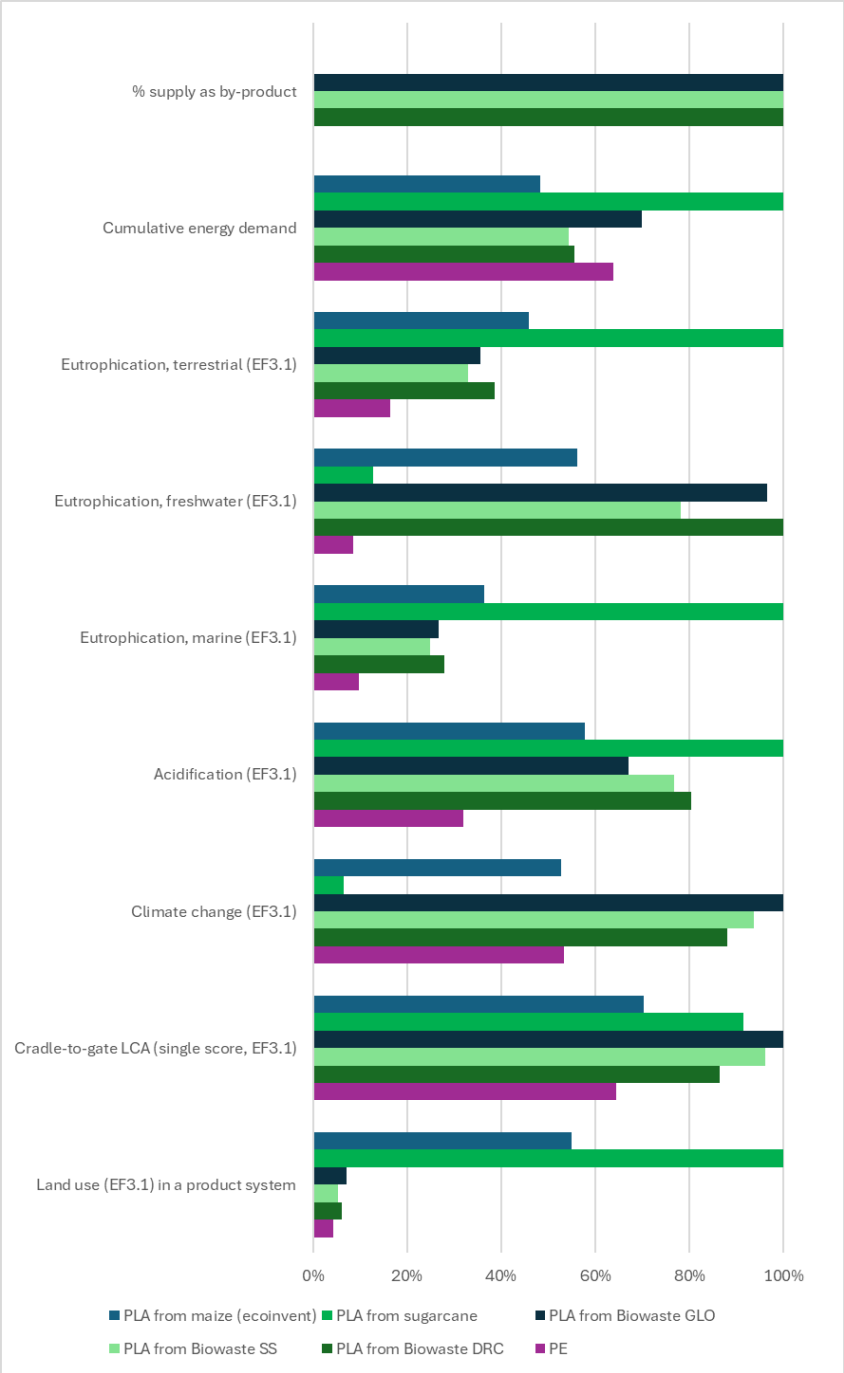


Figure 83 Material-related indicators for criticality assessment (the higher, the worse)

To conclude, each biotic resource presents its own set of issues to be tackled. From these indicators and the retrieved market shares, it seems that **maize is the least critical**. However, by **diversifying primary material type**, the PLA procurement criticality will be **more reliable**, and a larger set of suppliers and regions could be considered.

The criticality assessment also revealed **issues** related to the use of **biowaste** as biotic raw material. These are linked to food competition and pose new criticality issues: waste local supply chains to be set, instability of waste production in the

DRC and SS due to high scores in FSI, governance and economic instability, and high environmental impacts due to energy use.

Additionally, once PLA reaches HA target countries (the DRC and SS), it must be kept in mind that **distribution could also be a bottleneck**, limiting PLA wrapped items delivery to the HA field. Indeed, in Figure 84, it can be observed that distribution is a more important bottleneck than maize production, as the countries' performance values of interest are relatively high, due to the current crisis in these regions. Furthermore, distribution is limited to the country of destination, whereas production can rely on various countries performances. There are several examples of distribution disruption in the HA context. For instance, in SS the World Food Program published an article[75] in April 2025 where they say that "Fighting in some of the country's most food-insecure areas has reportedly displaced around 100,000 people, disrupted food deliveries and forced WFP to pause distributions in several counties – cutting off critical humanitarian aid to some of South Sudan's most vulnerable communities." Even though the rest of HA supply chain was controlled, the final step of distribution was hindered and rendered impossible.

[75] https://www.wfp.org/stories/people-south-sudan-deserve-freedom-prisons-conflict-and-hunger

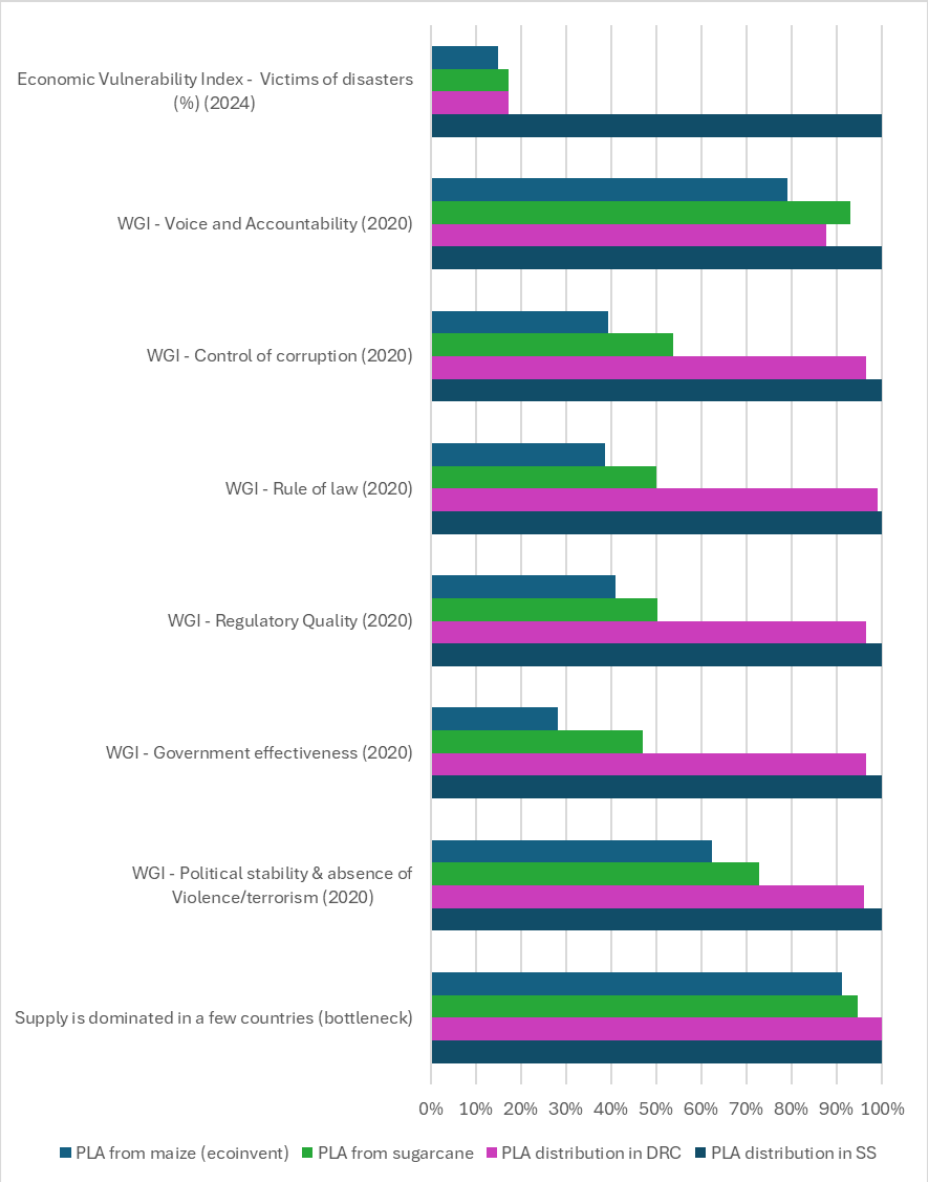


Figure 84 Criticality assessment of PLA distribution in DRC or in SS, compared to PLA production, from maize or sugarcane (the higher, the worse)

8. Mitigation measures

To avoid criticality issues due to PLA packaging, there are a few recommendations:

- Diversifying PLA biotic resources: different resources imply different regions and less dependency on specific suppliers.
- Foster biowaste use in developed countries (e.g. China, USA, etc.) but avoid dependency on local production in the DRC and SS, where food competition, waste management issues and governance issues could arise.
- It might be interesting to keep polyethylene as a fall-back material in case of PLA supply chain disruption.

To **further analyse** the situation, it would be interesting to examine other production stages, such as manufacturing (plastic transformation process) or shipping, and to update the country performance with **more recent data**. Also, other criticality

indicators might be interesting to complete the study in the future: Environmental Performance Index (environmental policy targets implementation), Natural disaster Index, labour conditions, expected demand growth, primary material use, etc. In the scope of Bio4HUMAN, criticality methodology could be valuable for other items and packaging materials.

VII. Conclusion

The LCA of reference materials and biobased solutions highlighted similar environmental hotspots across the life cycle: Climate Change, Resource Use, fossils, Particulate matter, Resource Use, minerals and metals, and Photochemical ozone formation. Some categories are more specific to certain materials: Human Toxicity and Acidification for fossil-based plastics, or Water Use and freshwater Ecotoxicity for bio-based alternatives. Overall, **EoL** had a **significant impact on the reference** scenario but was **not as important** in the impacts related to the bio-based and biodegradable **solution** materials.

Regarding **PLA** material, the **least impactful** way of obtaining PLA is by **recycling** it, chemically or mechanically. However, in the case of virgin PLA, biowastes or crops as biotic resources can present different advantages, depending on process waste valorisation or implementation of a co-production. It is essential to **select a PLA supplier carefully**, and a synthetic table for virgin PLA selection is elaborated on in this deliverable. PLA-based material presented interesting properties of durability (MDI) and limited effect on biota due to plastic scattering. Nevertheless, it is important to stress that **PLA is not universally biodegradable**: studies show that incomplete degradation is likely, and it can lead to persistent **microplastic fragments**. Even though PLA leakage is less impactful on biota than polyethylene, proper collection and treatment of PLA waste under **controlled composting** conditions is still **important to avoid ecosystem quality degradation**.

In addition, **composting**, even when capturing around 90% of the biogenic carbon, still results in about 10% of the carbon being released, half of which as **methane** (CH_4). Given methane's high global warming potential, this remaining fraction has significant **climate impact**. Controlling moisture and improve **ventilation** can help reduce CH_4 emissions. Also, alternatives such as anaerobic digestion or other future waste digestion solutions (e.g., biochar production) should be further considered as more sustainable pathways.

Industrial compost infrastructures do not exist in the DRC or SS, but their implementation can be relatively simple and does not require large-scale facilities. Small, decentralized composting units, already demonstrated in countries like Ghana[76], could represent a **feasible solution in humanitarian contexts**, if adequate training and follow-up are ensured.

Building materials showed diverse impacts at different stages: glass wool is penalised by energy-intensive raw materials, bio-based polyurethane foams by raw

[76] Ghana: ejemplo mundial en reciclaje » GRÜN Engineering

material inputs and its open burning, cellulose by open burning and mineral additives, hemp by its electricity demand, and sheep wool by animal emissions and feed requirements.

Alternative waste treatment routes such as **anaerobic digestion and BSF** bioconversion were also assessed. These pathways can generate valuable by-products (biogas, nutrient-rich digestates) but also present drawbacks (energy use, post-composting emissions). Furthermore, a complementary assessment revealed that their overall **environmental performance strongly depends on the local context**, including the electricity mix and the impossibility of compost valorisation in urban areas. To sum up, these waste treatment solutions, particularly anaerobic digestion, provide **consistent solutions** and benefits for HA camp. However, they are not yet available in the HA field, so the infrastructure would need to be implemented considering the local constraints (see D5.1 for more information on the matter).

Additional studies on environmental risk sensitivity to the geography were conducted. First, it was assessed that the energy mix of the DRC and SS can affect the materials environmental hotspots if produced locally. Secondly, the impact of **transportation distances during EoL** does not induce significant differences in materials cradle-to-grave impacts, so this variable is **not a significant environmental issue**, even though local waste treatment remains preferable.

Beyond environmental aspects, the role of geographical constraints was explored during the development of D5.2. To **reduce dependency and criticality risks of PLA** procurement, proposed **strategies** include diversifying PLA feedstocks and promoting bio-waste valorisation in developed countries rather than in fragile regions.

It must be emphasized that the purpose of this deliverable was **not to compare solutions with the references** directly, which will be the **objective of D5.3**, but rather to identify and analyse the main environmental hotspots. This objective has been achieved, providing a robust basis for subsequent comparative work. Moreover, it should be noted that the data used for modelling were mainly generic “market for” datasets, which inherently include distribution steps. No site-specific data were considered in this deliverable, which represents a limitation of the current analysis but also a clear avenue for improvement in future research and projects.

Finally, the upcoming analysis (D5.3) will build on the work of this task T5.2 to support policymakers in their choices based on environmental aspects. This will guide humanitarian organisations in choosing the most suitable materials under given conditions, while integrating supply risk and sustainability issues. In this way, the project establishes the basis for more sustainable and resilient material and packaging management in HA operations.

VIII. Annexes

See D5.2 ANNEXES file.

A. EU projects review

1. ALIGNED

a) Project Overview

b) Environmental Indicators Promoted in the Project

c) Methodology for Indicator Calculation

d) Relevance to Our Project

2. BioRADAR

a) Project Overview

b) Environmental Indicators Promoted in the Project

c) Methodology for Indicator Calculation

d) Relevance to Our Project

3. CALIMERO

a) Project Overview

b) Environmental Indicators Promoted in the Project

c) Methodology for Indicator Calculation

d) Relevance to Our Project

4. LCA4Bio

a) Project Overview

b) Environmental Indicators Promoted in the Project

c) Methodology for Indicator Calculation

d) Relevance to Our Project

B. Inventories updates

1. **PLA inventories**
2. **Packaging and items solutions**
    - *a) Food kit*
    - *b) Agricultural kit*
    - *c) WASH kit*
    - *d) Non-Food Items (NFI) kit*
    - *e) Building insulation*
    - *f) EoL by compost*
3. **EoL solutions**

C. LCIA Methodologies

1. **European Footprint 3.1 methodology**
2. **ReCiPe 2016 Endpoint methodology**
3. **Impact World+ methodology**