D5.3

Identification of the best available innovative solutions based on environmental LCA

Due date: 31/12/2025

Responsible partner: WeLOOP

Disclaimer:

The analyses and results presented in this deliverable are based on generic and representative life cycle inventory datasets. These datasets reflect typical market conditions and standard production processes. The outcomes of the assessment may differ if more specific, context-dependent, or supplier-verified data become available. Consequently, the conclusions and recommendations provided should be interpreted in light of these data limitations and may require revision as more accurate information emerges.

Document information

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*R — Document, report; DMP — Data Management Plan; DATA — data sets, microdata, etc; DEC —Websites, patent filings, videos, etc.

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7.	18/12/2025	WeLOOP	Integration of PIN, PAH and PRO CIVIS's comments, final version

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Publishable Summary

Deliverable 5.3 presents a comparative environmental assessment of the materials currently used in humanitarian aid kits and the innovative bio-based solutions identified within the Bio4HUMAN project. Building on the life cycle inventories established in D5.1 and the hotspot analysis in D5.2, this deliverable evaluates the environmental performance of both reference and bio-based items using harmonised functional units and updated reference flows. The assessment covers individual items (such as mosquito nets, containers, sanitary pads) or packaging materials, and four standard humanitarian kits: Agriculture, Food, WASH, and Non-Food Items (NFI). All comparisons rely on the Environmental Footprint 3.1 (EF3.1) method, complemented by indicators that capture biodiversity and plastic leakage impacts.

Across all kits, the results show that the main contributors to environmental impacts are the core items: fertilisers and seeds in the Agriculture Kit, flour and rice in the Food Kit, tents in the NFI Kit, and multipurpose cloth and buckets in the WASH Kit. Tertiary packaging generally accounts for only 2–5% of total impacts. Bio-based solutions can provide meaningful improvements for certain items (for example, PLA mosquito nets, PLA oil containers, and reusable sanitary pads). But they can also increase impacts when higher material quantities are required, such as when substituting large polypropylene or polyethylene bags with multiple small PLA bags. The performance of some bio-based materials is therefore strongly dependent on their mechanical strength, load capacity, and suitability for large-volume applications.

End-of-life (EoL) management emerges as a decisive factor shaping environmental outcomes. Open burning and open dumping (common in acute crisis and protracted crisis settings) drive significant impacts in particulate matter, toxicity, and biodiversity damage driven by plastic leakage. Bio-based, compostable materials offer clear advantages only when supported by appropriate disposal conditions.

This deliverable concludes that while bio-based packaging and materials can support environmental improvements in humanitarian operations, the most effective strategies lie in optimising high-impact items, improving material performance, and strengthening end-of-life systems. A separate roadmap (D5.3 - Annex) provides detailed, actionable recommendations for humanitarian organisations, highlighting priority actions at item, packaging, and kit levels.

List of Abbreviations

Abbreviation	Meaning
μPt	micro (10^-6 unit) points
B4H	Bio4HUMAN
DRC	Democratic Republic of Congo
DX.X	Deliverable X.X
EF3.1	Environmental Footprint 3.1 (LCIA methodology)
EoL	End-of-Life
EPS	Expanded PolyStyrene
EU	European Union
FU	Functional Unit
HA	Humanitarian Aid
HDPE	High Density polyethylene
HO	Humanitarian Organisations
IW+	Impact World + (LCIA Methodology)
kgCO2eq	kilogram CO2 equivalent
L	Liter (Volume)
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LDPE	Low density polyethylene
MDI	Material Durability Indicator
NFI	Non-Food Items
P (on graph)	Packaging
PBAT	PolyButylene Adipate Terephthalate
PDF·m²·yr	Potentially Disappeared Fraction of species over an area during a year
PE	Polyethylene
PLA	PolyLactic Acid
PP	Polypropylene
PU(R)	Polyurethane
PVC	Poly Vinyl Chloride
R	Thermal Resistance
RUTF	Ready-to-Use Therapeutic Food
SS	South Sudan
U.S.	United States
WASH	Water, Sanitation and Hygiene
WP	Bio4HUMAN Work Package

I. Introduction

A. Background and Positioning within WP5

The Bio4HUMAN project aims to identify, assess, and promote sustainable material solutions that can reduce the environmental burden of humanitarian aid (HA) operations while maintaining the performance, safety, and usability of essential items delivered to crisis-affected populations. Within this context, WP5 evaluates the environmental performance of both the existing (reference) materials currently used in humanitarian supply chains and the innovative bio-based solutions identified by project partners.

Deliverable 5.1 compiled the relevant Life Cycle Inventory (LCI) data for all reference items and proposed bio-based alternatives, structured by item category and kit type (Food, WASH, Agriculture, and Non-Food Items). It also defined the detailed modelling assumptions for packaging systems, logistics pathways, and end-of-life (EoL) scenarios for the Democratic Republic of Congo (DRC) and South Sudan (SS), as documented in Annex 1 of D5.1.

Deliverable 5.2 extended this work through a hotspot analysis using the Environmental Footprint 3.1 (EF3.1) method and additional indicators relevant for bio-based materials (plastic's physical effect on biota, biogenic carbon uptake, ecosystem quality, and Material Durability Indicator (MDI)) thereby identifying the most impactful life cycle stages and processes for each material group.

The present deliverable builds directly on D5.1 and D5.2. It provides a comparative Life Cycle Assessment (LCA) of the reference materials currently used in humanitarian kits and the innovative bio-based solution items considered in the project. Each bio-based solution item is compared to its corresponding reference item under a harmonised functional unit (quantity of a product needed to deliver a specific function), followed by a kit-level assessment that integrates the contribution of all items included in the Food, Agriculture, WASH, and NFI kits. The comparative results are examined across all EF3.1 midpoint categories and the additional indicators introduced in D5.2, offering a comprehensive view of potential environmental trade-offs and improvements. Since the solution EoL technologies (anaerobic digestion technologies and Black Soldier Fly) were already assessed and compared in D5.2, they are not further analysed here; this deliverable focuses exclusively on solution items.

The scope, system boundaries, EoL scenarios, inventory assumptions, and modelling parameters used in the present assessment remain aligned with those established in D5.1 and D5.2. These aspects are therefore not reiterated in detail in the present document. Instead, this deliverable focuses on aspects required to move from hotspot identification to comparison: (i) definition of item- and kit-specific functional units, (ii) harmonised comparison between reference and solution materials, (iii) quantification of net environmental impacts at both item and kit scales.

B. Purpose of this deliverable

The objective of this deliverable is therefore threefold:

1. **Quantitatively compare** the environmental impacts of reference items and their proposed bio-based solutions, using a harmonised LCA framework consistent with the Bio4HUMAN methodology.
2. **Identify key environmental trade-offs**, highlighting the conditions under which bio-based solutions outperform or underperform reference items (e.g., under different EoL scenarios or raw material selections).
3. **Provide science-based recommendations** to humanitarian organisations and donors on the environmental implications of material substitution choices, supporting more sustainable procurement strategies.

C. Structure of this deliverable

- Section II introduces the methodological elements specific to the comparative study, including the functional units and comparison logic.
- Section III presents the comparative LCA results at the item level, accompanied by interpretation and identification of trade-offs.
- Section IV aggregates the results at the kit level, analysing the combined environmental performance of each kit.
- Section V examines additional environmental indicators (such as ecosystem quality and plastic effects on biota) to provide a broader understanding of how bio-based and fossil-based materials affect biodiversity and microplastic risks.
- Section VI summarises the key conclusions and provides recommendations for HA actors.

Through this comparative assessment, the deliverable offers critical insights to support decision-making for more sustainable and resilient humanitarian aid supply chains.

II. Methodological Framework

This section outlines the methodological elements specific to the comparative LCA conducted in this deliverable. Since Deliverables 5.1 and 5.2 already define in detail the system boundaries, modelling assumptions, inventory sources, and impact assessment methods used in the Bio4HUMAN LCA framework, these aspects are not reiterated in this document. Instead, this section clarifies the additional aspects required to compare reference items with their corresponding bio-based solutions.

A. Goal and Scope

The objective of this deliverable is to assess whether the bio-based materials and packaging solutions identified in Bio4HUMAN offer measurable environmental benefits compared to the fossil-based reference items currently used in humanitarian operations. The comparison is carried out at two levels of:

- Item-level performance, where individual reference items are compared directly to their respective bio-based alternatives.
- Kit-level performance, where all items included in a humanitarian kit (Food, WASH, Agriculture, NFI) are aggregated to evaluate the overall environmental impact of the complete kit.

B. Functional Unit and Reference Flow

Unlike D5.2, where 1 kg of each material is used to identify environmental hotspots, this deliverable implements functional units that reflect the actual service provided by each item in their specific context (humanitarian operations):

1. Item-level functional units (FU)

Based on the comments and feedback received from humanitarian organisations (PIN and PAH), both the functional units (FUs) and their corresponding reference flows (quantity required to fulfil each FU) were revised for this deliverable. The updated definitions ensure better alignment with the actual use conditions, typical quantities distributed, and operational requirements of the humanitarian kits.

In this assessment, the FU is defined per item delivered to a beneficiary with its full intended functionality, and the complete list of FUs applied in this study is presented in Table 1:

Table 1 Functional units and reference flows of different kit items

Item	Functional Unit (FU)	Reference flow – Bio-based solution	Reference flow – Reference scenario
Water container	10-litre water container(s) capable of storing and dispensing water for one month	5 x 2L PLA bottles = 5 x 69 g= 345 g	1 x 10 L PE bottle = 210 g
Oil container	6-litre oil container(s) capable of storing and dispensing edible oil	3 x 2L PLA bottles = 3 x 69 g= 207 g	2 x 3 L HDPE bottle = 2 x 157 g= 314 g
Adhesive tape	1 m² of adhesive tape	50.7 g of bio-based adhesive tape	54.56 g of regular tape
Laminating film	1 m² of film to be used as tertiary packaging	37.2 g of bio-based film	27.6g of LDPE film

Item	Functional Unit (FU)	Reference flow – Bio-based solution	Reference flow – Reference scenario
Compostable sachet for RUTF	To contain 92 g RUTF	4.2g of RUTF pouch	5g of RUTF pouch
Disposable bag	To contain 10 kg	10.621 g/bag* 50 bags (each having 0.2 kg capacity) = 531 g	8.17 g of HDPE film and 2.52g of PP film= 10.69g
Insulation material	To thermally insulate 1 m^2 of surface with an R=1 W/m^2K	2.6kg of glass wool	• 1.72kg of bio-based PUR foam • 1.1kg of sheep wool insulation • 1.76kg of hemp-based insulation • 1.3kg of cellulose-based insulation
Sanitary pads with wings	240 pads covering the needs of a menstruating person for one year	9.5 g/pads* 4 pads/cycle *5days/cycle*12 month= 2.28 kg of pads material	Disposable: 10 g/pads * 4 pads/cycle * 5 days/cycle * 12 month = 2.40 kg of pads material Reusable: 2 pads per year, each used twice per cycle = 0.6 kg[1]
Mosquito net	Provide protection for one person for one year	206.4 g of polyester mosquito net	240.8 g of PLA mosquito net

2. Kit-level functional units (FU)

For full kits, the FU is defined as:

One complete kit delivered to a household (responding to the need of a family with 2 adults and at least 2 children for one month), containing all standardised items as defined in D5.1 Annex 1.

This includes:

- Food kit
- WASH kit
- Agriculture kit

[1]Typically, a 2 set of pads is provided by the HOs which includes 10 pads in total for the lifetime of 5 years. Therefore, it's assumed that 2 pads are used annually to respect the time frame of the functional unit.

- Non-Food Items kit.

C. Inventory Sources and Alignment

The Life Cycle Inventories (LCIs) used in this comparative assessment are directly derived from:

- D5.1 baseline inventories (items, packaging, material datasets, logistics modelling, and EoL datasets)

- D5.2 corrected inventories, incorporating methodological and dataset updates

D. Impact Assessment Methods

The comparative assessment relies on the same impact categories and additional indicators selected in D5.2 to ensure methodological consistency across WP5. Therefore:

1. Environmental Footprint 3.1 (EF3.1)

All 16 midpoint categories described in D5.2 Section III.A are used in this deliverable.

Results are presented using a single–score metric. In LCA, a single score represents the aggregated environmental impact of a product or system expressed as a unique indicator. It is obtained by normalising, weighting, and combining all characterised impact categories, such as climate change, resource depletion, toxicity, and water use, into a unified metric.

This approach facilitates interpretation and supports decision-making by placing diverse environmental effects on a comparable scale. While the single score simplifies interpretation and supports decision-making, it is important to remember that it reflects methodological choices (e.g., weighting factors and normalisation references) and therefore, it should be interpreted together with the underlying impact category results for a complete understanding of the environmental performance.

2. Additional indicators

As introduced in D5.2, two additional indicators are included to capture sustainability dimensions not reflected in EF3.1:

- **Plastic's physical effect on biota** (Impact World+), quantifying microplastic-related biodiversity risks

- **Ecosystem Quality** (endpoint indicator, Impact World+), aggregating impact categories into damages on ecosystem quality.

These indicators complement the EF 3.1 results and support a more comprehensive evaluation of bio-based materials in humanitarian contexts. Ecosystem quality aggregates the all the impact categories into damages on ecosystem quality and displays how biodiversity can be affected by the fossil- or bio-based materials. Plastic effect on biota is also selected as it underlines the issues associated with lack of plastic waste management.

III. Items Comparison Analysis

In this section, the reference materials and proposed bio-based solutions are compared using a single score that reflects each option's overall environmental impact. In LCA, a single score is obtained by aggregating the different impact categories (such as climate change, water use, resource depletion, and toxicity) into a single value. This makes it easier to compare materials at a glance. Although this simplifies interpretation, it is important to remember that a single score combines many impact types into one number. Therefore, results should still be complemented with category-specific analyses. In this deliverable, such detail is included where relevant; for a more comprehensive breakdown across all impact categories, readers should refer to Deliverable 5.2.

A. Mosquito Net

Figure 1 presents the comparison between the reference mosquito net (made from woven polyester fibres coated with pesticide) and the PLA-based solution, in which the fibre material is substituted. The results indicate that the PLA-based option delivers approximately 26% lower overall environmental impacts. This improvement is primarily driven by reductions in key categories such as climate change, fossil resource use, and human toxicity (non-cancer). The only category where the solution performs worse than the reference is water use, reflecting the agricultural water demand associated with maize cultivation for PLA production.

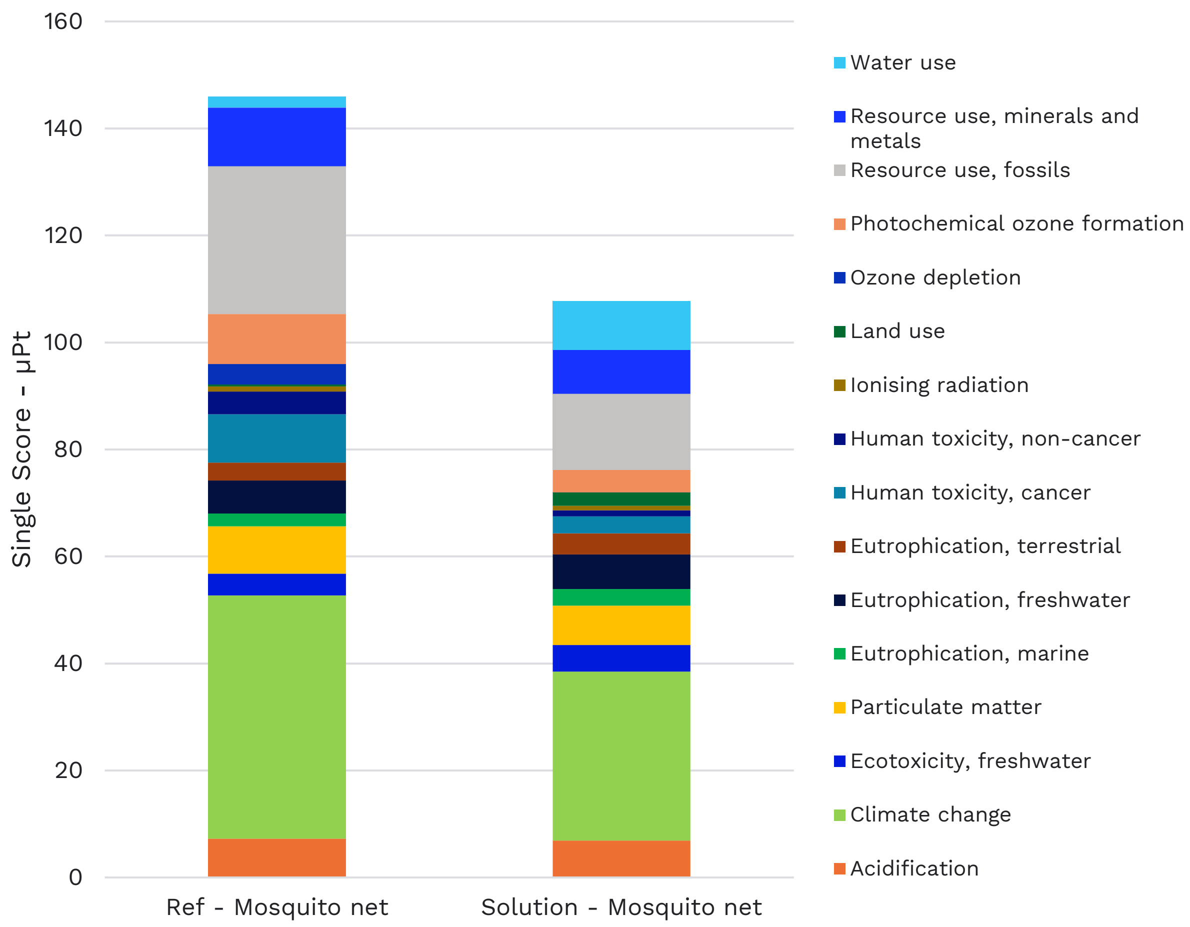

Figure 1 Single score comparison of 1 piece of Mosquito net

For the reference mosquito net, nearly 80% of total impacts stem from polyester fibre production, with the remaining impacts driven largely by EoL open dumping. In contrast, the PLA-based solution concentrates about 90% of its impacts in the production stage, while its EoL (modelled as industrial composting) accounts for only 10% of the total score. Notably, the solution's EoL impacts are approximately 70% lower than those of the reference material, highlighting the environmental advantage of compostable materials over non-compostable plastics that are typically dumped.

Although the PLA-based mosquito net appears to be a suitable replacement from an environmental perspective, further justification is needed regarding its technical performance. The originally proposed PLA-based solution was a fishing net, characterised by larger mesh openings, whereas mosquito nets require a much finer mesh density to ensure adequate protection. Nonetheless, this design constraint is expected to be manageable through appropriate adjustments in manufacturing.

B. Oil Container

Figure 2 compares the reference oil containers (two 3-litre HDPE jerrycans) with the proposed solution of three 2-litre PLA containers, providing the same total capacity of 6 litres. The results show that the PLA alternative achieves approximately 29% lower overall environmental impacts (single score). This improvement is driven by reductions in major categories, such as climate change and fossil resource use, reflecting PLA's lower fossil dependency relative to HDPE. The only category where the solution performs worse than its reference is water use, due to the agricultural water demand associated with maize cultivation for PLA feedstock.

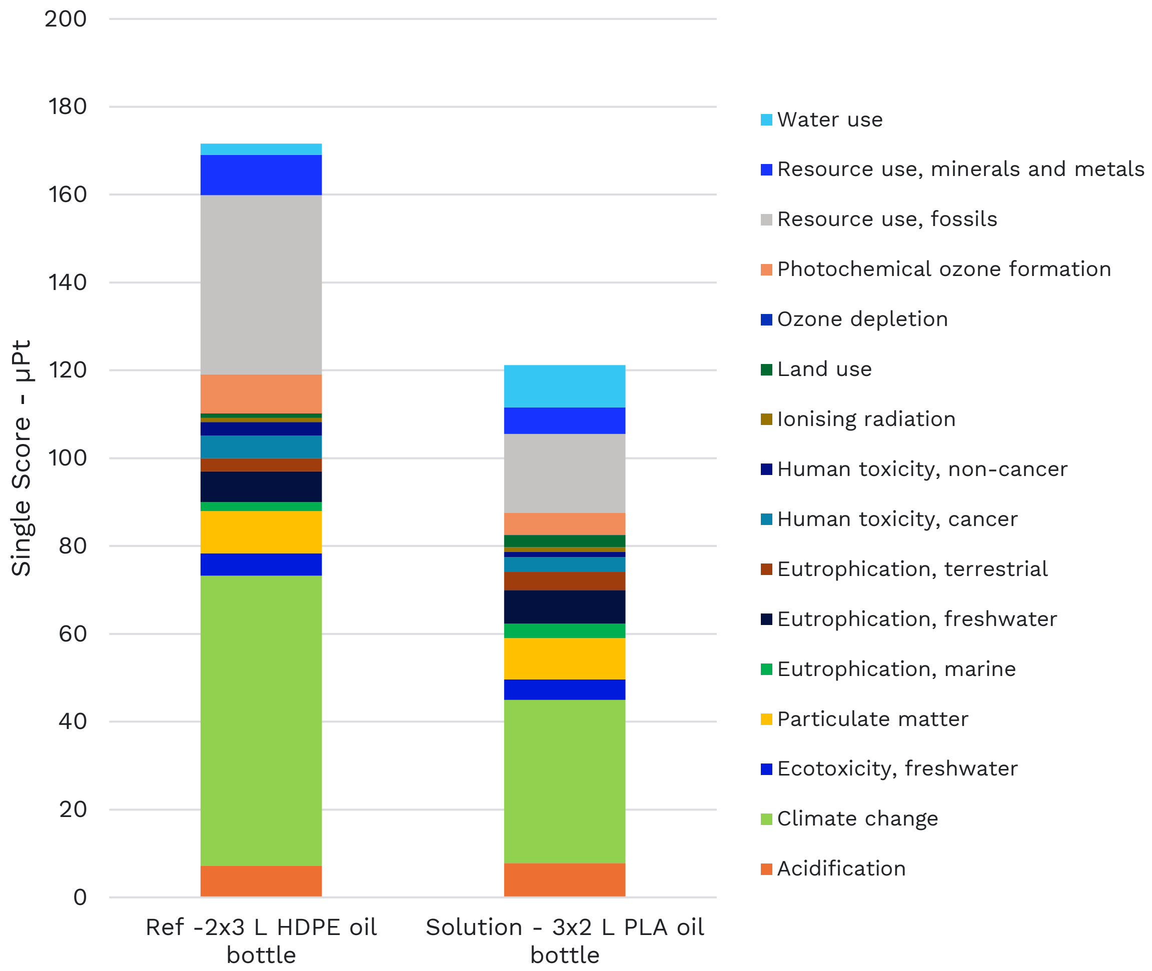

Figure 2 Single score comparison of the oil container

For the reference item (HDPE containers), around 83% of total impacts arise from the production phase, including raw material extraction and plastic transformation processes, with the rest linked to the EoL stage. The PLA-based solution shows a similar pattern, with about 93% of its impacts originating from raw material production and transformation. However, its EoL impacts are significantly lower: the EoL burden of the 3×2 L PLA containers is approximately 75% lower than that of the 2×3 L HDPE jerrycans.

Overall, the PLA solution clearly performs better across most key impact categories, with its main trade-off being water use - a limitation inherent to agricultural feedstocks.

C. Water Container

Figure 3 presents the single score comparison between the reference 10-litre LDPE jerrycan and the proposed solution consisting of five 2-litre PLA bottles. Unlike the previous examples where PLA-based materials generally outperformed fossil-based alternatives, the PLA option shows approximately 80% higher overall impacts. This difference is primarily due to the greater total mass of material required for the PLA solution (345 g) compared to the LDPE container (210 g). The additional weight compensates for PLA's lower mechanical strength, which currently prevents the production of larger single-volume containers. As the bioeconomy sector has not yet reached the maturity of fossil-based plastics, ongoing innovation in biodegradable materials continues to drive progress; as a result, future advances in PLA formulations may enable lighter, more robust bottles, potentially reducing this performance gap.

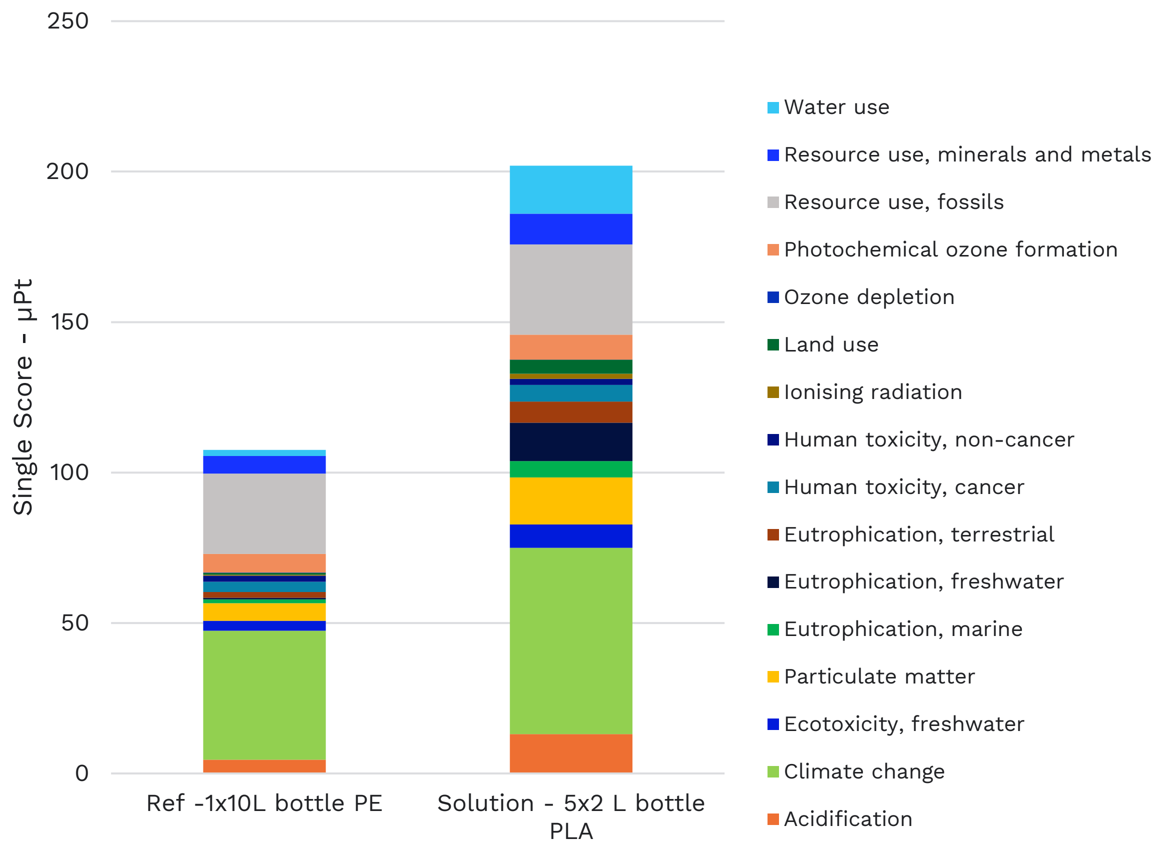

Figure 3 Single score comparison of the water container

For the reference LDPE jerrycan, around 83% of total impacts originate from the production stage, including raw material extraction and plastic transformation, with the remainder attributable to EoL treatment. The PLA-based solution shows a similar pattern, with about 93% of impacts linked to raw material sourcing and manufacturing. However, its EoL burden is 37% lower than that of the 10L LDPE container, as the PLA bottles are treated through industrial composting.

Consistent with its higher single score result, the PLA solution shows higher impacts across most categories due to the greater material mass required. However, if a single 10 L PLA container could be produced (lowering the total mass to fulfil the functional unit), the total impacts would likely be much lower and closer to those of the reference. This highlights that the environmental performance of PLA packaging depends strongly on optimising size and material efficiency, rather than simply substituting fossil-based materials.

D. Sanitary Pads (Disposable and Reusable) with Wings

Figure 4 presents the single score comparison among the reference disposable sanitary pads (made from a mixture of cellulose superabsorbent polymer, PE and PP - 240 units), the bio-based disposable pads made from organic cotton (240 units), and the reusable pads (2 units). The quantities refer to the needs of 1 person for 1 year: 20 single-use pads per cycle (240 per year) and 2 reusable pads per year, each used twice per cycle.[2] The bio-based disposable pads show 9% higher overall impacts than the reference option, largely because cotton cultivation accounts for nearly 90% of their total environmental impacts. While the reference pads have lower production impacts, their EoL stage represents 45% of the total burden, mainly due to open burning. In terms of category-specific performance, the reference material scores higher in climate change, particulate matter, human toxicity, and fossil resource use, whereas the cotton pads show higher eutrophication[3] and land use impacts linked to agricultural activities.

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[2] The performed comparison is under one FU and a comparable use-case scenario. It is understandable that under conditions of emergency, limited water access, lack of privacy or facilities for washing/drying the use of disposable pads is the only option and makes the comparison senseless.

[3] The addition of nutrients to water in lakes and rivers, which encourages plant growth that can take oxygen from the water and kill fish and other animals.

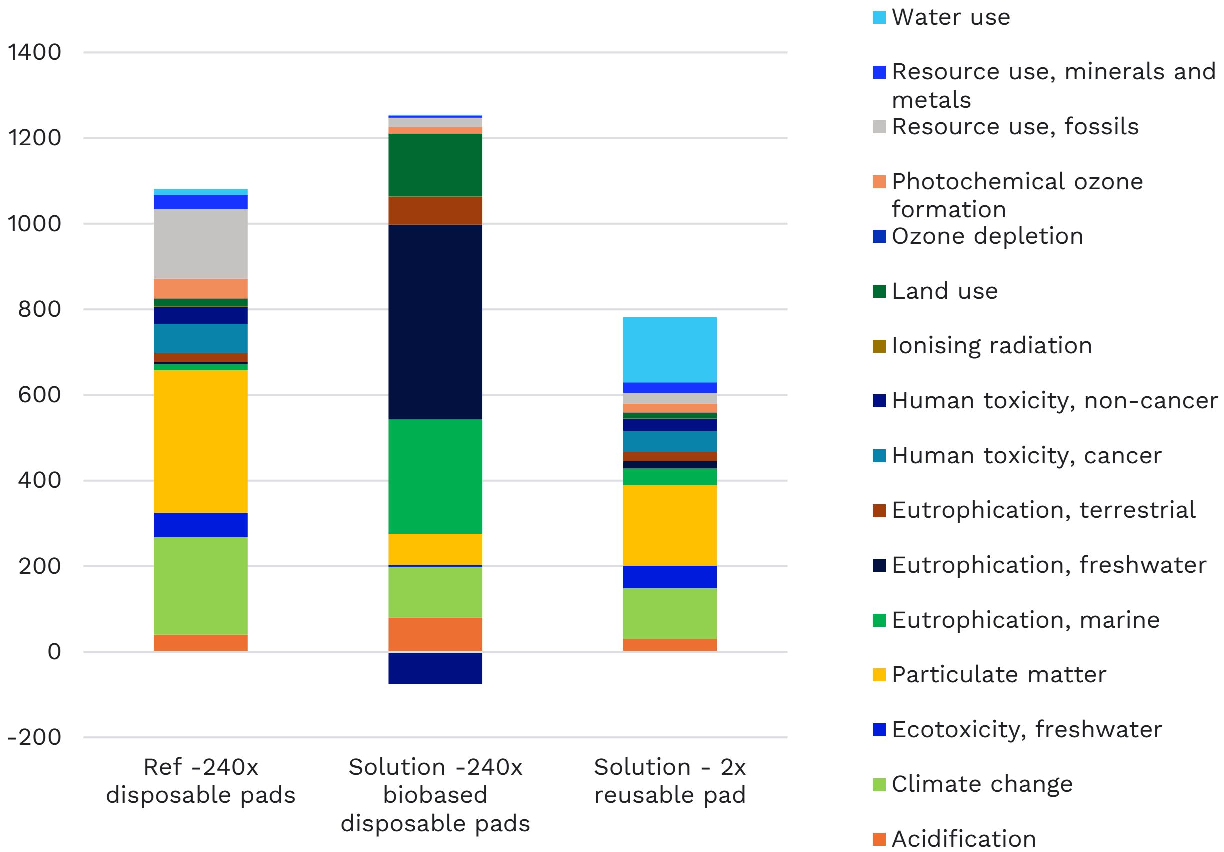


Figure 4 Single score comparison of sanitary pads

A notable result is the negative human toxicity (non-cancer) value for the cotton pads, which arises from the ability of the cotton plants to take up certain heavy metals (divalent cations such as Cadmium, Zinc, Lead, Nickel, Mercury) from the soil. Within the EF 3.1 method, this removal is modelled as an environmental benefit and therefore appears as a negative score.

The reusable pads perform best overall, showing 27% lower impacts compared with the reference pads. Around 45% of their total impacts stem from washing, which is reflected in their higher water-use impact. Their EoL contributes only 7% of the total impact, compared with 45% for the reference disposable pads and 5% for the bio-based disposable solution.

EoL treatment drives substantially different impacts across the three products: the bio-based pads show EoL impacts mainly as climate change, while the reference pads show much higher impacts in particulate matter and human toxicity due to open burning. This highlights that improved waste management, such as industrial composting or controlled disposal, could substantially reduce the EoL burden of disposable sanitary products.

E. Adhesive Tape

Figure 5 presents the single score comparison between the reference PVC adhesive tape and the biodegradable adhesive tape used for secondary packaging of items. The results show that the bio-based tape has approximately 8% lower overall impacts than the PVC-based alternative. For the PLA-based solution, most of the impacts originate from PLA production, driven by maize cultivation, and from natural rubber (acquired from rubber tree) used in the adhesive layer. In contrast, the reference tape is dominated by PVC production impacts and a particularly burdensome EoL stage, as open dumping.

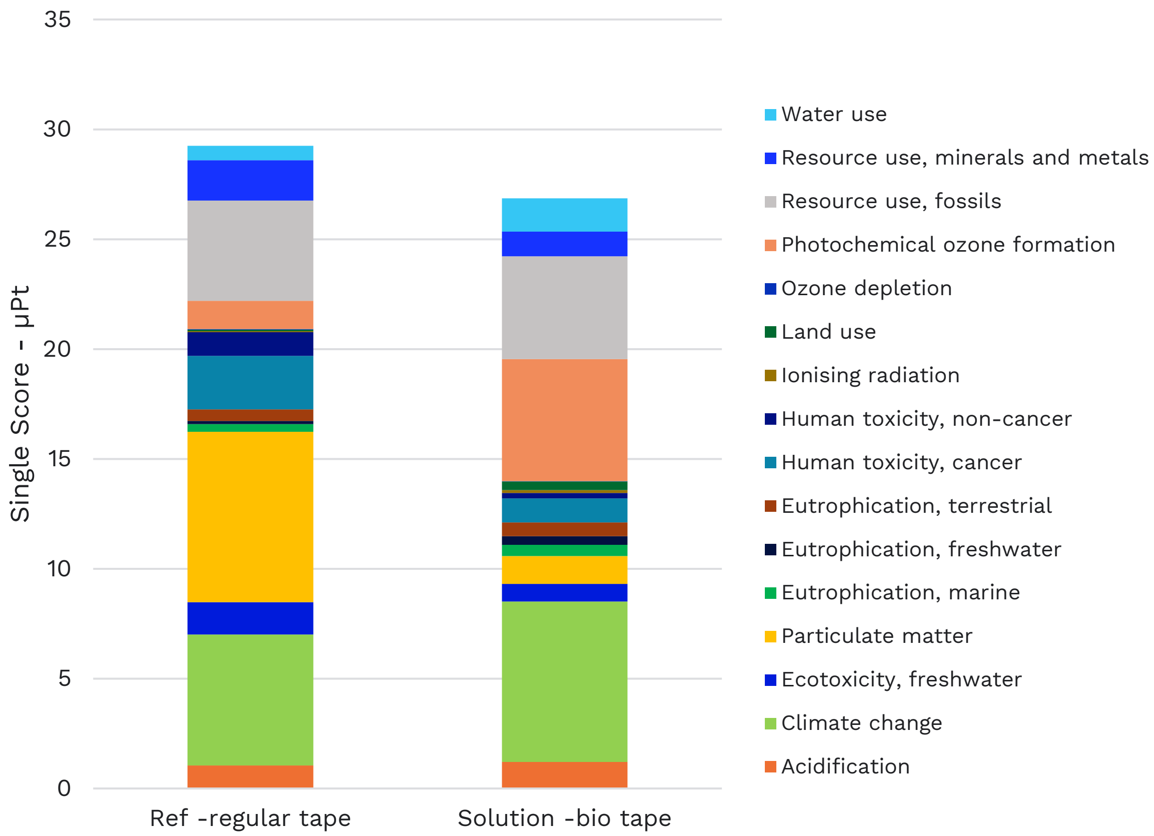


Figure 5 Single score comparison of adhesive tape

The PLA-based tape shows slightly higher impacts in climate change and photochemical ozone formation, largely linked to the sealing layer. However, the reference tape exhibits a heavier EoL burden: around 40% of its total impacts stem from open dumping, compared with only about 6% for the bio-based tape, which undergoes industrial composting. This indicates that, despite similar overall impact levels in some categories, the EoL profile of the bio-based tape is lower.

F. Buildings Insulation

Figure 6 compares the single score results for 1m² of insulation across all materials, each delivering an equivalent thermal resistance of R = 1 W/m²·K. Among all options, bio-based PUR foam shows the highest impacts, mainly due to its energy-intensive chemical synthesis, and the production of polyols, isocyanates, and catalysts, which drive burdens in climate change, fossil resource use, and toxicity-related categories.

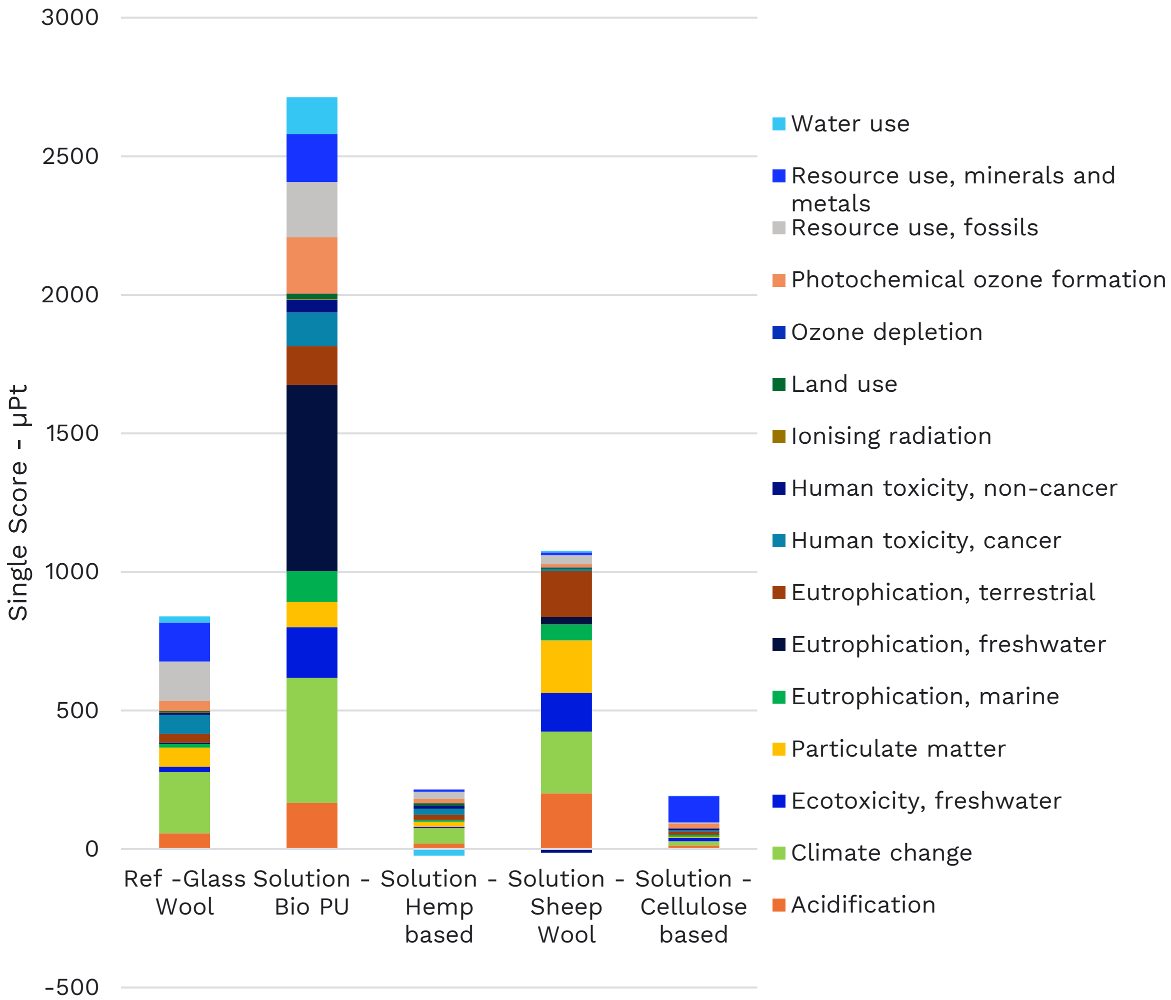


Figure 6 Single score comparison of building insulation

Glass wool and sheep wool show moderate impacts, although for different reasons. Glass wool is dominated by the energy-intensive melting and fibre-forming process, whereas sheep wool is largely driven by livestock-related emissions (methane, nitrous oxide, ammonia), resulting in higher contributions to climate change, acidification, and particulate matter formation.

In contrast, hemp- and cellulose-based insulations have the lowest overall impact. Hemp cultivation requires relatively few inputs, so its impacts primarily arise from electricity use during processing and EoL emissions. Cellulose insulation is produced mainly from recycled newspaper and carries negligible upstream burdens; its impacts stem mainly from additives (e.g., boric acid) and open-burning emissions at the EoL.

Regarding end-of-life, sheep wool is assumed to be composted, resulting in a negligible EoL contribution due to its slow biodegradability. Indeed, to represent sheep wool slow degradation compared to most plant-based materials: all carbon is considered to stay in the ground at EoL, so climate change impacts of this EoL is particularly low. In contrast, hemp, cellulose, and bio-PUR foam are treated through open burning. For cellulose insulation, EoL accounts for 38% of total impacts, mainly in climate change, acidification, and photochemical ozone formation. For hemp and bio-based PUR, EoL contributes 27% and 24%, respectively, with significant effects on climate change and photochemical ozone formation. The reference product, glass wool, shows only a 3% EoL contribution, reflecting its relatively inert composition.

All insulation materials are assumed to be disposed of through open burning or composting, meaning that recycling or alternative EoL solutions, if available, would likely yield significantly lower impacts, making these results a conservative estimate. Although insulation materials are not directly applicable for humanitarian contexts in the DRC or South Sudan, this comparison remains relevant for other regions where building insulation is required particularly in protracted crisis or reconstruction contexts involving semi-permanent/durable housing (e.g. Ukraine, Nepal, Pakistan, Lebanon, Armenia, Moldova).

G. Fragile Item Packaging

Figure 7 compares the single score performance of expanded polystyrene (EPS) and mycelium inserts, both designed to fit a standard U.S. Postal Service shipping box (31.12 × 30.48 × 15.24 cm). The EPS insert weighs 0.286 kg, whereas the mycelium insert requires 1.400 kg of material due to its higher density. Overall, Mycelium shows about 49% higher impacts.

EPS exhibits greater impacts on fossil resources due to its petroleum-based feedstock, while mycelium shows greater impacts on climate change, water use, and freshwater eutrophication due to fungal cultivation and substrate processing. Mycelium also contributes moderately to land use, whereas EPS has minimal land use impacts but a substantial reliance on fossil resources.

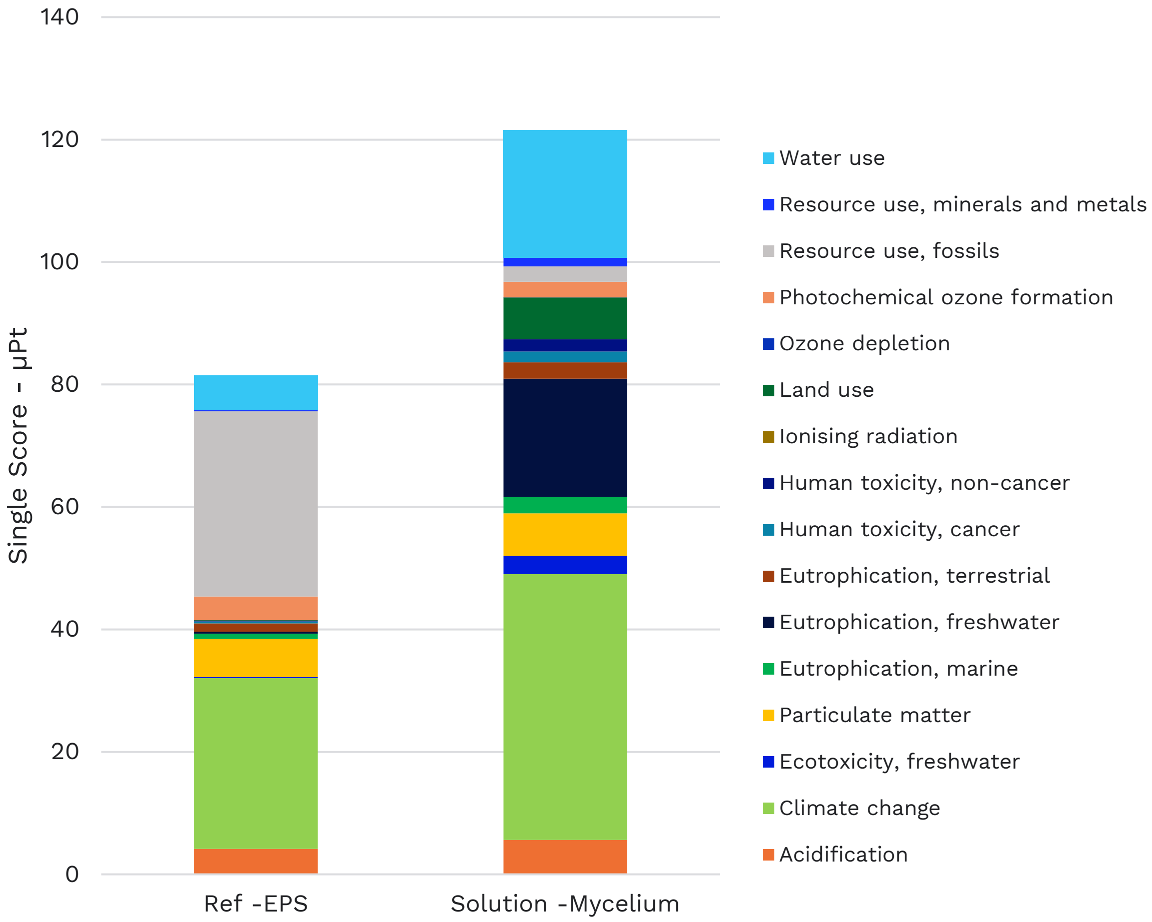


Figure 7 Single score comparison of cushioning materials

Although the mycelium inserts with a similar size have higher environmental impacts, they perform significantly better on a per-kilogram basis. The greater density of the current mycelium configuration means that more material is required to achieve the same protective volume, as already illustrated in Deliverable 5.2.

Importantly, two recent LCA studies reinforce this trend: Enarevba & Haapala (2023)[4] found that mycelium-based packaging inserts generally have lower environmental impacts than EPS, particularly with respect to energy demand and carbon footprint despite some category-specific trade-offs such as ozone depletion. Similarly, Zoungrana et al. (2025)[5] demonstrated that lower-density mycelium foams (e.g., MBF50) show substantially reduced impacts across most midpoint categories such

[4] Enarevba, D. R., & Haapala, K. R. (2023). A Comparative Life Cycle Assessment of Expanded Polystyrene and Mycelium Packaging Box Inserts. *Procedia CIRP*, *116*, 654–659. https://doi.org/10.1016/j.procir.2023.02.110

[5] Zoungrana, A., Hausner, G., & Yuan, Q. (2025). Sustainability assessment of mycelium bio-foam packaging compared to expanded polystyrene through environmental impact assessment. *Discover Sustainability*, *6*(1), 1119. https://doi.org/10.1007/s43621-025-02025-8

as global warming and toxicities, confirming that optimising density can give mycelium a clear environmental advantage over EPS.

Therefore, if the density of the mycelium insert were reduced - allowing a bulkier but lower-mass configuration, the environmental impacts would decrease substantially. It is also important to note that EoL impacts were not assessed for either material in this comparison, due to the lack of specific EoL data for the mycelium product provided by the solution supplier. Inclusion of EoL performance could further shift the comparison, given the compostability potential of mycelium-based materials.

H. Pouch for RUTF materials

Figure 8 presents the single score comparison between the reference RUTF pouch (5 g containing 92 g of product) and the bio-based solution (4.2 g for the same capacity). Overall, the two alternatives show similar total environmental impacts, though with distinct impact profiles. The bio-based pouch achieves lower climate change impacts, largely due to its biogenic content and compostable end-of-life pathway. However, it exhibits higher particulate matter impacts, primarily linked to the production of metallised cellulose, PLA, and PBAT layers, which together contribute significantly to its upstream environmental burdens.

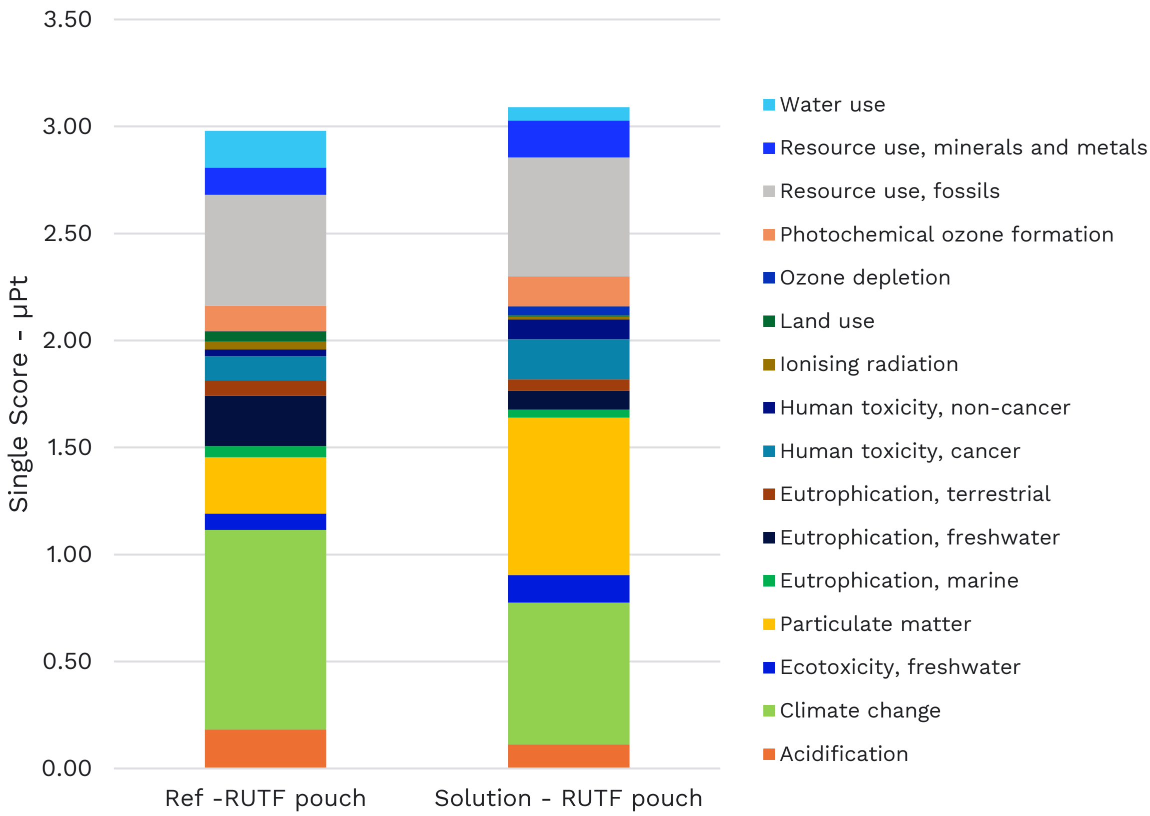


Figure 8 Single score comparison of RUTF pouch

Despite its lower weight, the bio-based pouch still struggles to outperform the reference across several impact categories because some of its components (especially the metallised cellulose barrier layer) involve energy- and material-intensive production processes. These upstream contributions limit the overall advantage the solution can achieve relative to the fossil-based pouch.

End-of-life treatment further differentiates the two options. For the reference pouch, open dumping accounts for around 38% of total impacts. In contrast, the compostable pouch, when treated through industrial composting, shows an EoL contribution of only about 3% of total impacts.

Overall, the bio-based pouch offers end-of-life benefits, but the energy-intensive production process of its barrier layers prevents it from delivering a clear environmental advantage over the reference pouch at this stage of development.

I. Bags for primary packaging materials

Figure 9 presents the single score comparison between the reference disposable bag, capable of carrying 10 kg of products in a single unit, and the bio-based PLA solution, which requires 50 individual bags of 0.2 kg capacity each to reach the same total load. This difference arises from the current performance limitations of pure PLA packaging: unlike polyethylene-based bags, PLA bags are not yet designed to handle bulk loads, necessitating their use in significantly smaller units. As a result, producing 50 PLA bags leads to 65% higher impacts than producing a single reference bag.

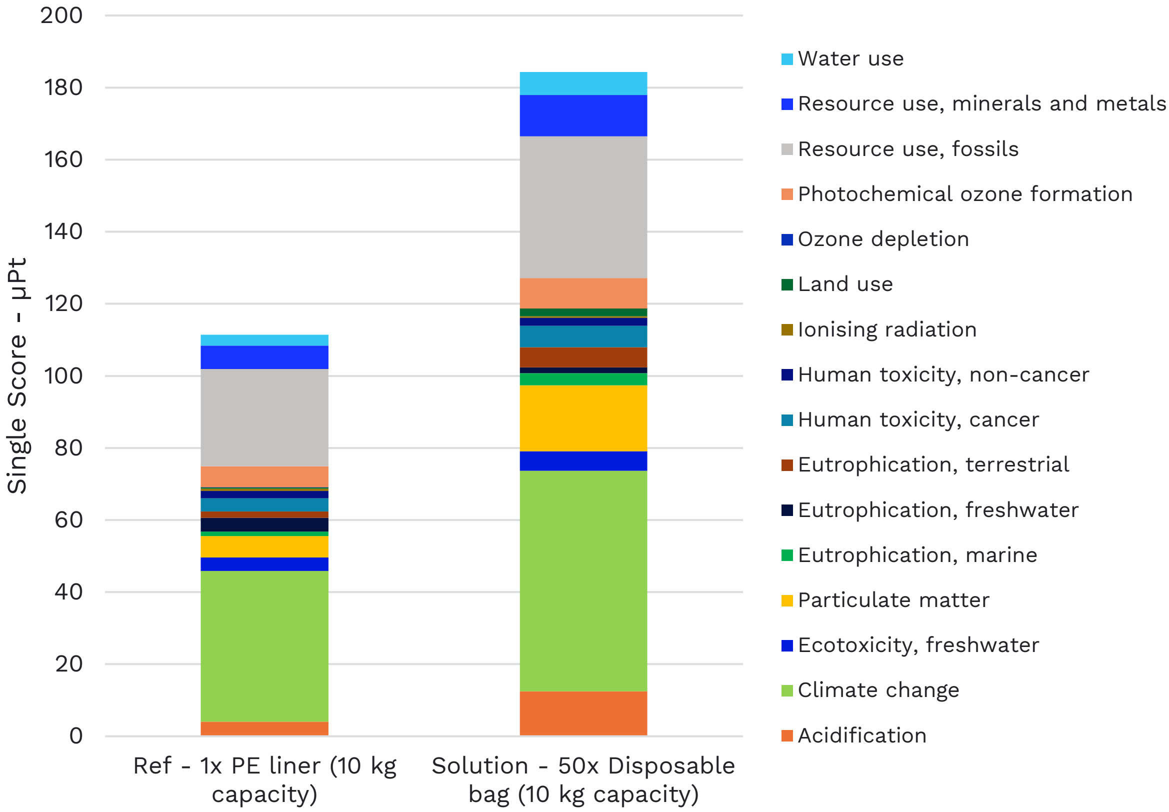


Figure 9 Single score comparison of Disposable bag (10 kg quantity)

However, when comparing one 0.2 kg capacity PLA bag to one 0.2 kg capacity PE liner (Figure 10), the PLA alternative shows lower overall impacts. A 0.2 kg PE liner weighs approximately 15 g compared to a 106 g for a 10 kg capacity PE liner. This demonstrates that the environmental drawback observed at the kit level is primarily functional -, the need for numerous small PLA bags, rather than an inherent limitation of the material itself.

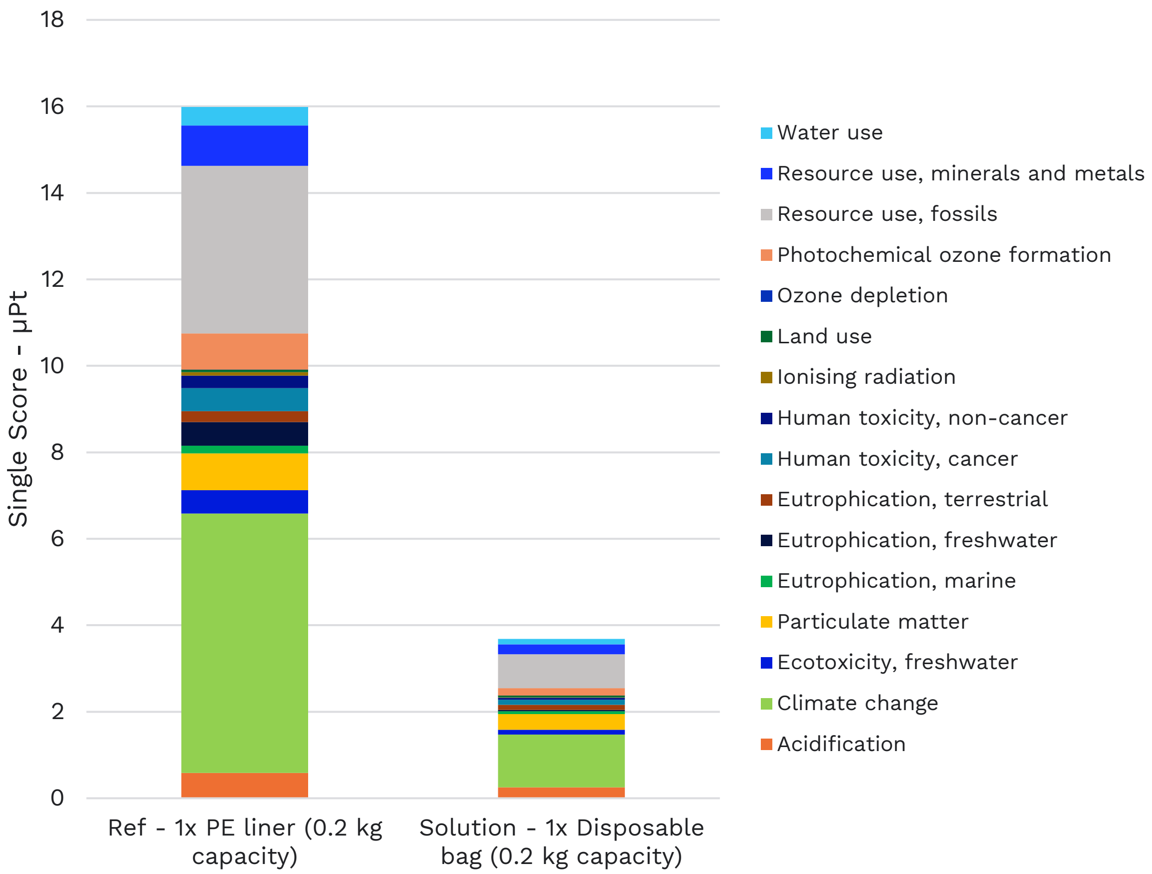


Figure 10 Single score comparison of Disposable bag (0.2 kg capacity)

In terms of EoL, the PLA bag's EoL accounts for about 12% of its total impacts, mostly associated with climate change. For the reference PE bag, the EoL contribution is around 10% and is dominated by climate change impact.

Looking forward, innovations in bio-based packaging, such as stronger PLA blends, fortifiers, and multilayer configurations, are expected to enable higher-capacity PLA bags. As research advances and market demand for compostable packaging grows, more robust PLA-based solutions are likely to emerge, reducing the need for multiple small bags and improving overall environmental performance. [6]

J. Laminating film for tertiary packaging

Figure 11 presents the single score comparison between LDPE laminating film and the biodegradable PLA-based laminating film, each assessed for 1 m² of tertiary packaging. The results show that the PLA film has approximately 20% higher overall

[6] *Relevant Horizon Europe and CBE-JU projects include **GRECO**, **NEWPACK**, **BioPackMan**, **Be-UP**, **USABLE PACKAGING**, **Bio2PEs**, and **UPLIFT**, all of which address improvements in compostable and bio-based packaging materials and their performance.*

impact than the LDPE counterpart. Although the PLA film performs better in climate change and fossil resource use, it has higher water use and land use impacts, largely due to the agricultural cultivation required for its bio-based feedstock.

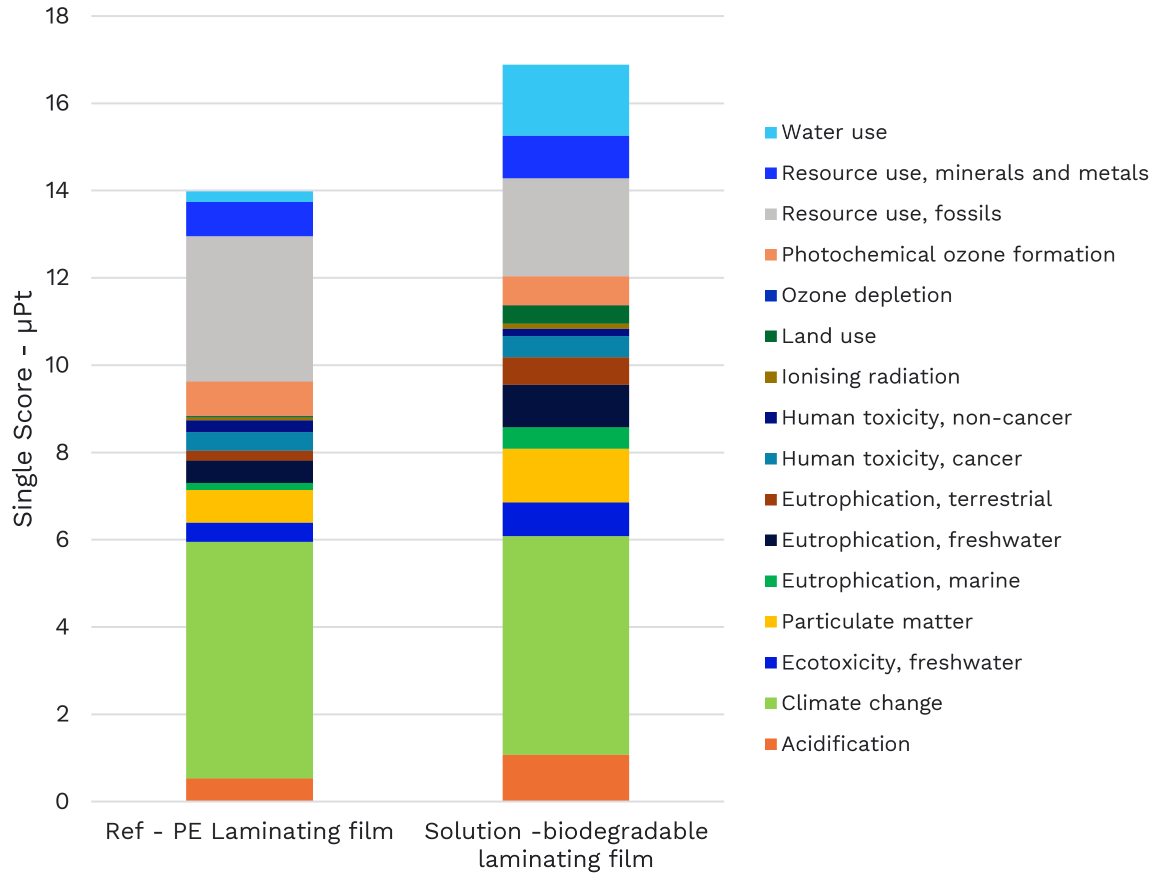


Figure 11 Single score comparison of laminating film

End-of-life treatment further differentiates the two options. For the biodegradable PLA film, the EoL stage accounts for around 9% of total impacts, primarily linked to climate change under an industrial composting scenario. In contrast, the reference PE film shows a higher EoL share of about 22%, mainly driven by climate-related emissions associated with open burning or dumping.

Despite the PLA option's higher overall impacts, both materials could achieve substantial reductions if produced from recycled feedstocks. Moreover, shifting toward controlled waste management such as recycling, rather than open burning or landfilling, would significantly improve the environmental performance of both laminating films, particularly the bio-based alternative, whose advantages become more evident under optimised EoL conditions.

IV. Kits Comparison Analysis

In the previous section, reference and bio-based items were compared to evaluate their respective environmental impacts. However, to fully understand the significance of these differences, it is necessary to assess the performance of each item within the context of its corresponding humanitarian kit. This approach allows for a clearer understanding of how individual items contribute to the overall kit impacts and the extent to which bio-based alternatives can influence total environmental performance. Such an analysis helps prioritise actions that can lead to the most meaningful impact reductions. Accordingly, this section analyses the different humanitarian kits using reference items to assess their current environmental impacts and examines the potential improvements achieved when the proposed solution items and packaging are introduced. The transportation of items is already accounted for in the generic datasets used for the analysis; therefore, it is already reflected in the impact results for each item.

A. Agriculture Kit

Figure 12 presents the overall environmental impacts of the reference Agriculture Kit. The pie chart shows that fertiliser and crop seeds account for approximately 39% and 33% of the total impact, respectively. The remaining tools collectively account for around 20%. Overall, tertiary packaging accounts for only about 4% of the total impacts, confirming that packaging plays a relatively minor role compared with the agricultural inputs themselves.

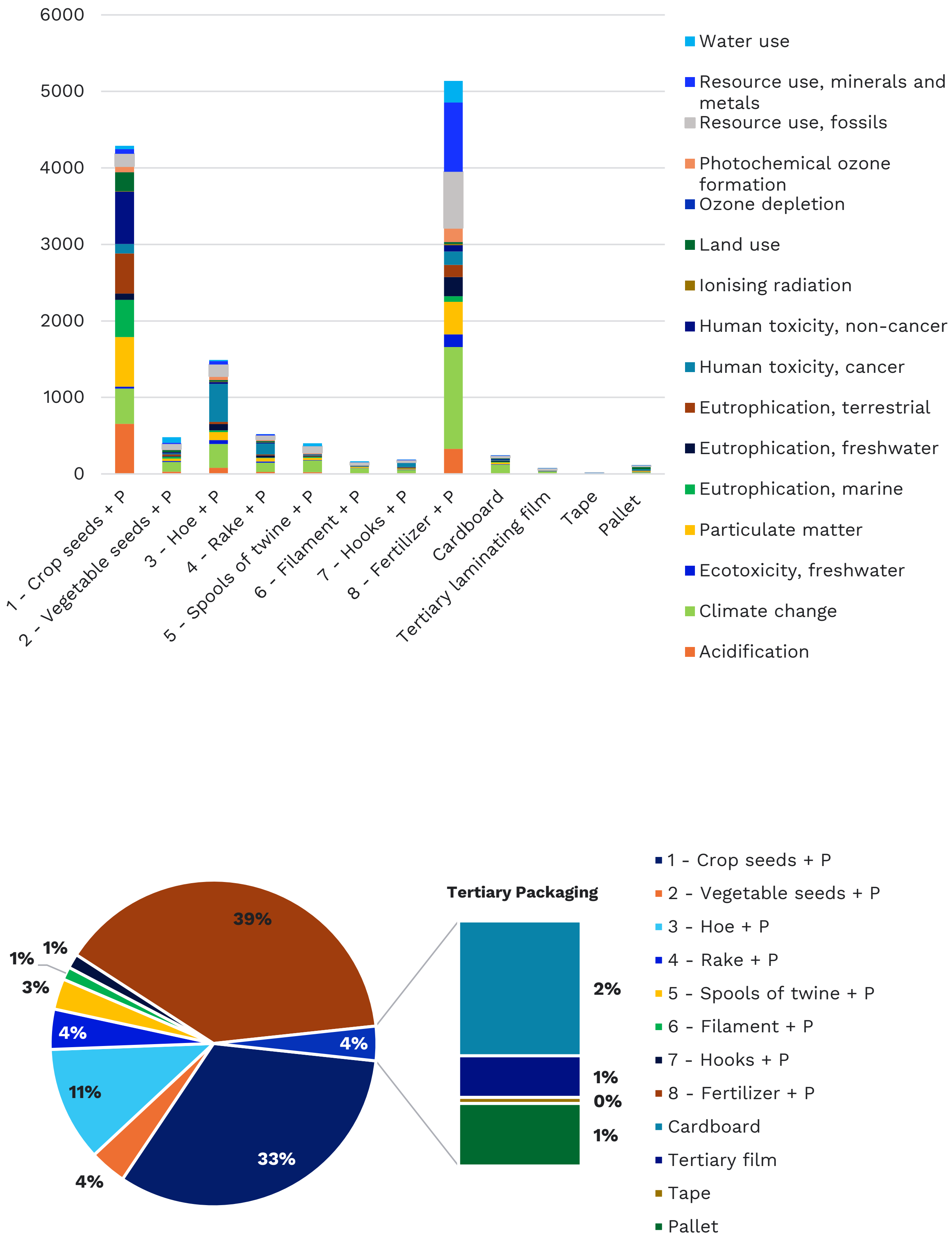


Figure 12 Reference agriculture kit overall impact and profile

Figure 13 shows the change in impacts resulting from replacing the reference packaging materials in the Agriculture Kit with the proposed bio-based alternatives. These percentages refer to the item-level impact, not the whole kit. At kit level, overall change remains small. Since the kit composition remains essentially unchanged, the results are attributable solely to the packaging substitutions.

The results indicate that the impacts associated with vegetable seeds decrease by approximately 18%, while those linked to the hoe decrease by approximately 4.5%.

However, the impact of crop seeds increases by about 2%, and the impact of fertiliser increases by roughly 3.5%, both driven by the need for larger quantities of biodegradable packaging to fulfil the same functional requirements. Additionally, replacing the LDPE tertiary film with a biodegradable laminating film raises its associated impacts by nearly 21%.

Changes for the other items were negligible since only a small portion of the content consists of packaging.

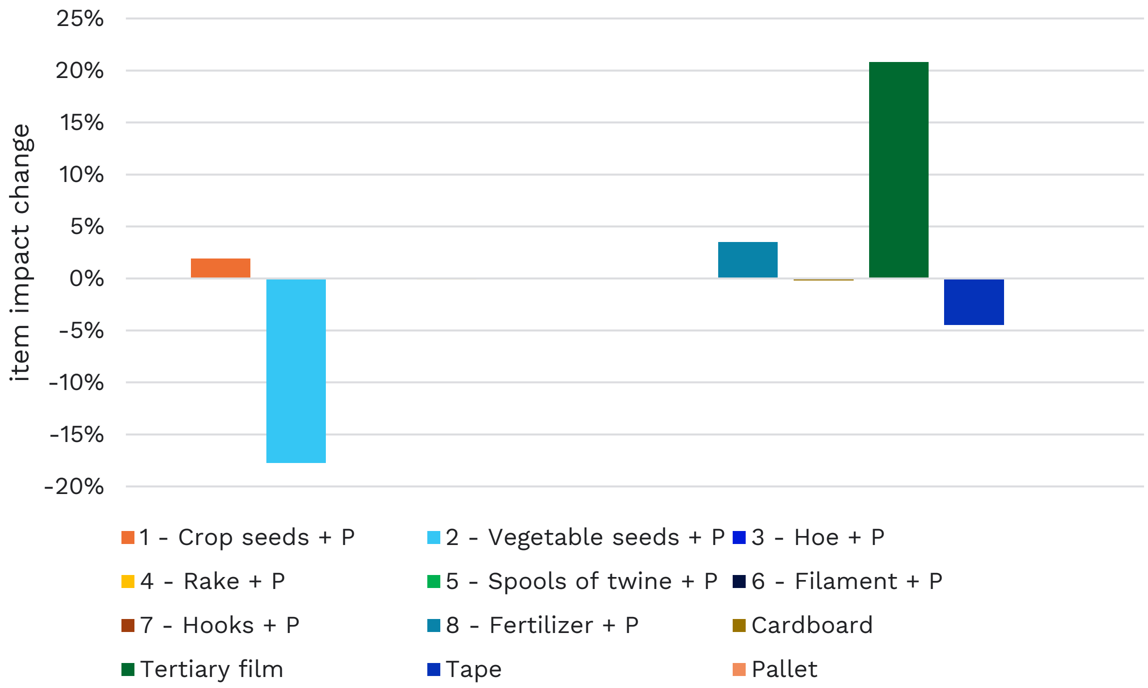


Figure 13 Agriculture kit comparative impact change: substitution of references with solutions

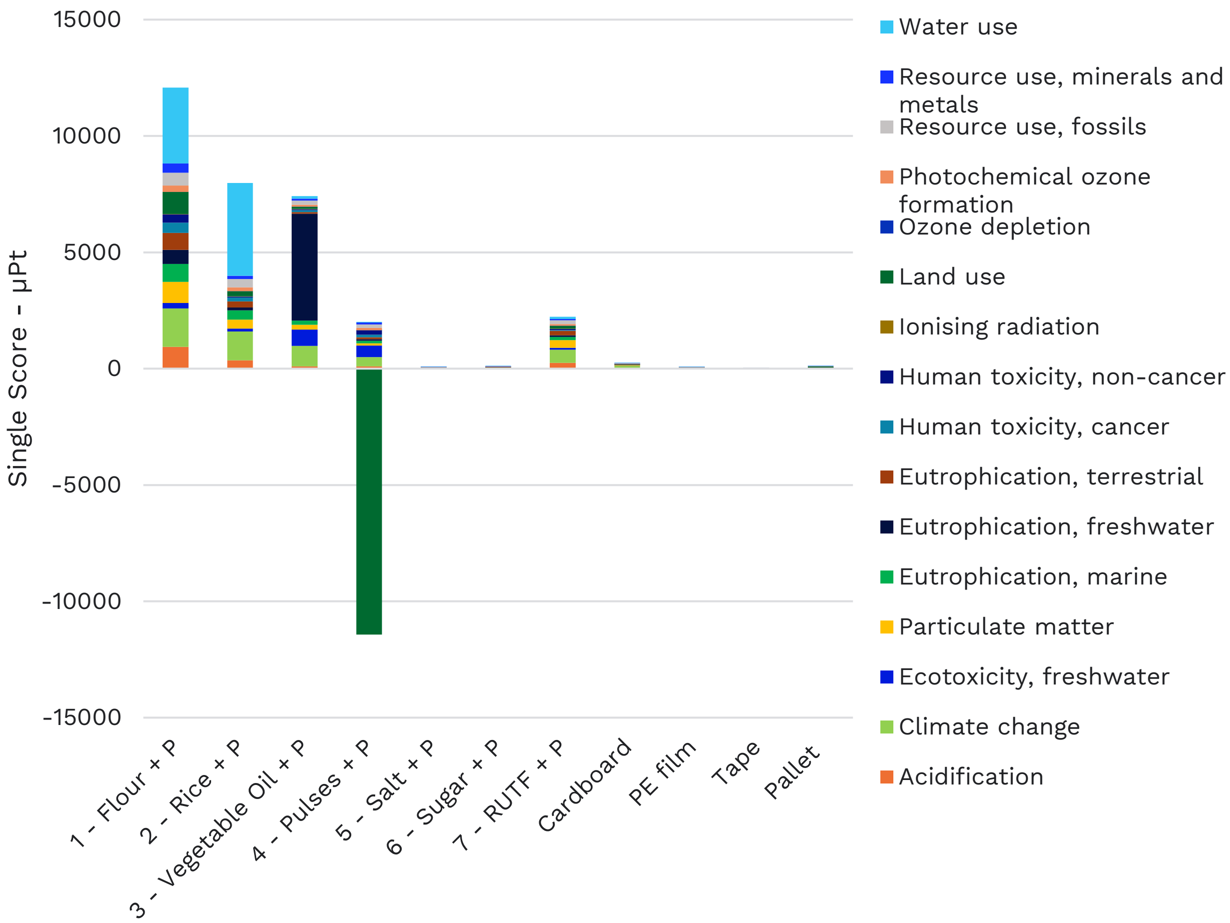
The Agriculture Kit's environmental footprint is drive primarily by the agricultural inputs (fertiliser and seeds), not packaging. Bio-based packaging can reduce impacts only in specific cases, mainly for small, lightweight items. However, for bulk items, it may increase resource use unless improvements in mechanical performance allow bio-based materials to meet functional requirements with lower material quantities in the future.

B. Food Kit

Figure 14 presents the overall environmental impacts of the Food Kit. The results show that flour (35%) and rice (20%) are the main contributors to the total impact, followed by salt (16%), vegetable oil (13%), and pulses (12%). The impacts of sugar and RUTFs are negligible. Pulses have comparatively low impacts, largely because they offer land-use benefits: as nitrogen-fixing crops, they require less fertiliser and often use land more efficiently than other staples. This reduces pressures associated with fertiliser production and soil degradation.

However, this does not imply that large-scale planting of pulses universally leads to environmental benefits; these advantages are context-dependent and can reverse if pulses replace native ecosystems or require irrigation in water-scarce regions.

Tertiary packaging of the materials also constituted less than 2% of total impacts, showing that the majority of the impacts are related to the items themselves rather than their packaging.



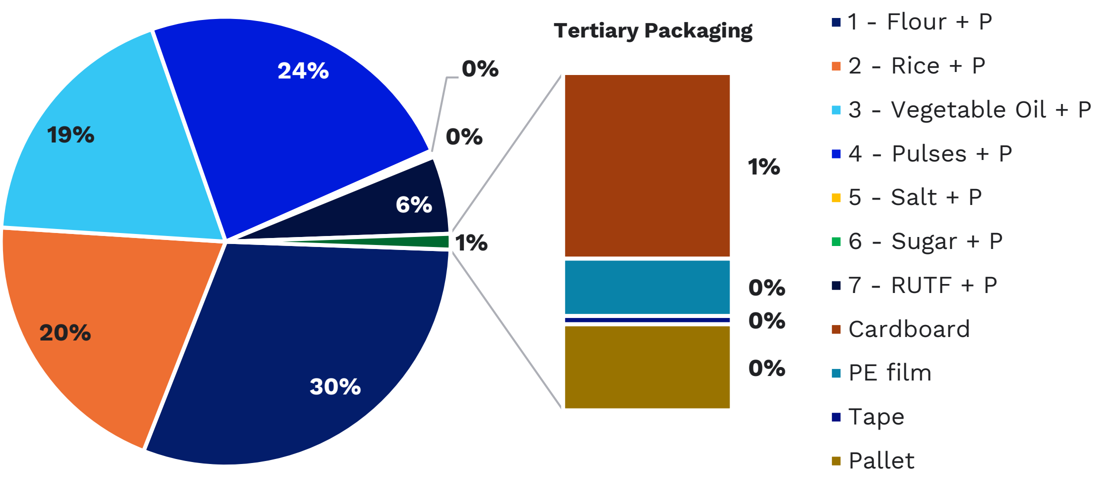


Figure 14 Reference food kit overall impact and profile

Figure 15 showcases the changes in impacts resulting from the implementation of the proposed solution packaging. Flour and rice show increases of 5.7% and 3.9% in impacts respectively, due to the high number of packaging units required. There is a slight reduction in the impacts of vegetable oil and pulses, but these changes are negligible.

Because the salt quantity in the Food Kit was only 1 kg, its impact was reduced by 64%, as not many disposable bags were used. Whereas the sugar quantity included in the food kit is 6 kg, additional disposable bags were required to replace the original PE/PP packaging, thereby increasing its overall impact. The RUTF packaging replacement did not present a high benefit regarding the overall life cycle. The tertiary film and adhesive tape also showed the same results as those in the Agriculture Kit.

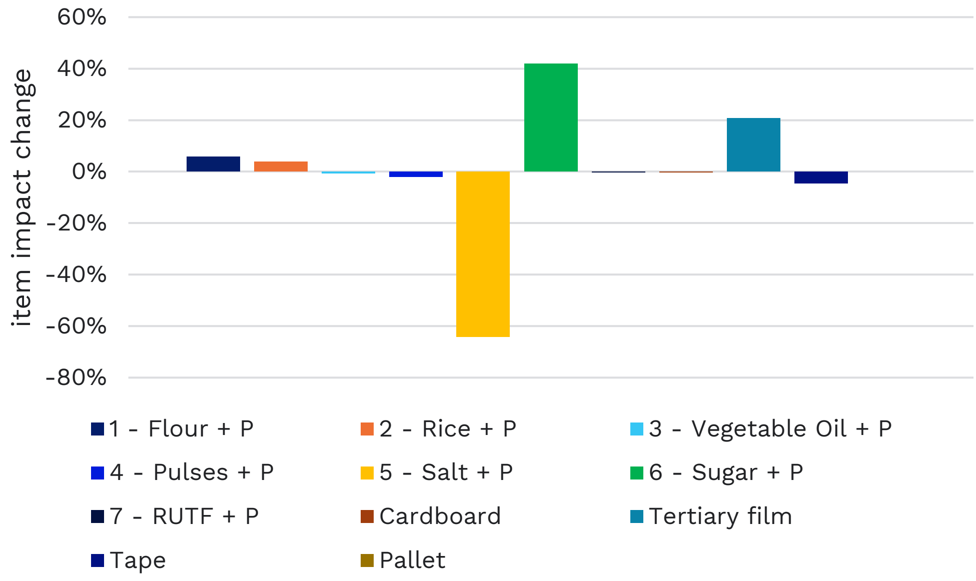
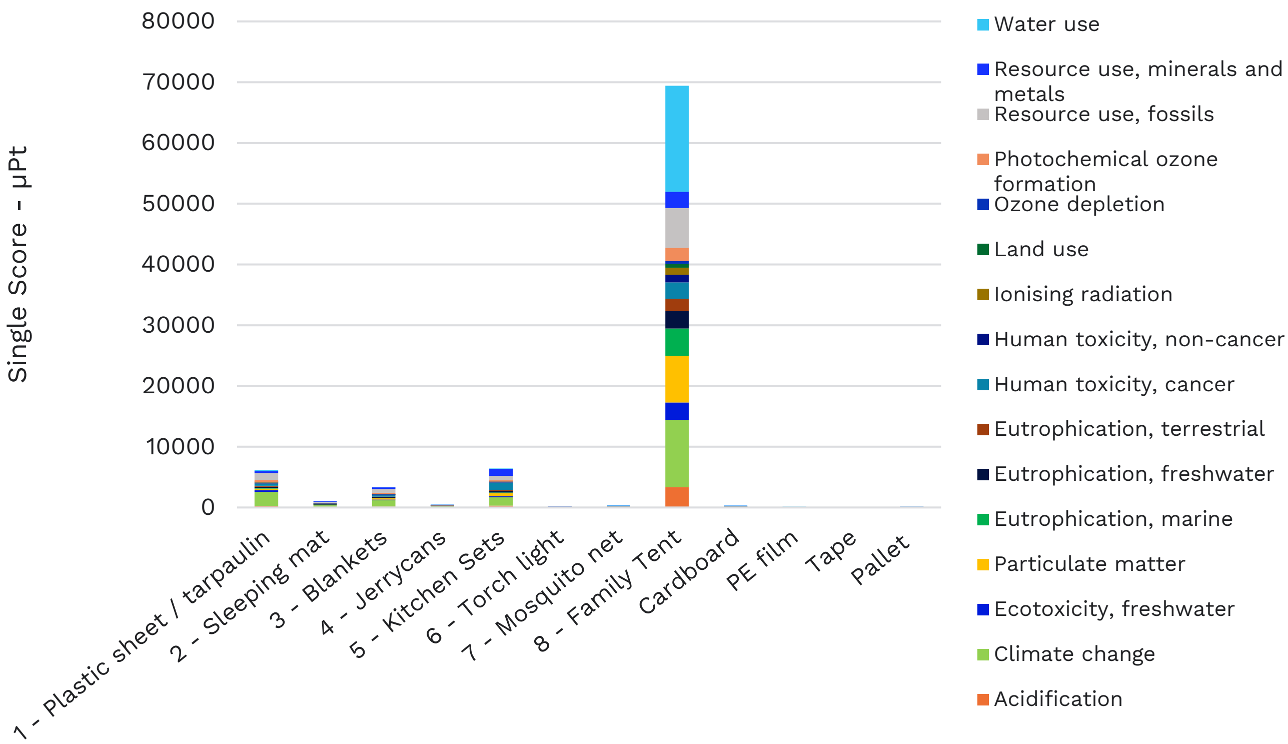


Figure 15 Food kit comparative impact change: substitution of references with solutions

The Food Kit's environmental footprint is driven almost entirely by the food commodities themselves, rather than their packaging. Bio-based packaging offers meaningful benefits only for small, low-volume items where functional performance is equivalent, while for bulk items (e.g., 5–25 kg goods), it can increase impacts due to the need for many smaller PLA bags. As with the Agriculture Kit, improvements in packaging materials provide only marginal gains; the most significant environmental reductions will come from optimising food sourcing, minimising packaging volume, and improving end-of-life handling.

C. NFI kit

Figure 16 presents the environmental profile of the reference NFI Kit, showing that impacts are heavily dominated by the family tent, which accounts for approximately 79% of the total footprint. This is expected, as the tent is a large, material intensive item weighing 36 kg and composed of steel frames, synthetic textiles, and heavy-duty waterproofing layers. After the tent, the next major contributors are the kitchen set (7%) and the plastic tarpaulin (7%), followed by the blanket and the sleeping mat. Packaging plays a negligible share of the NFI kit's environmental burden.



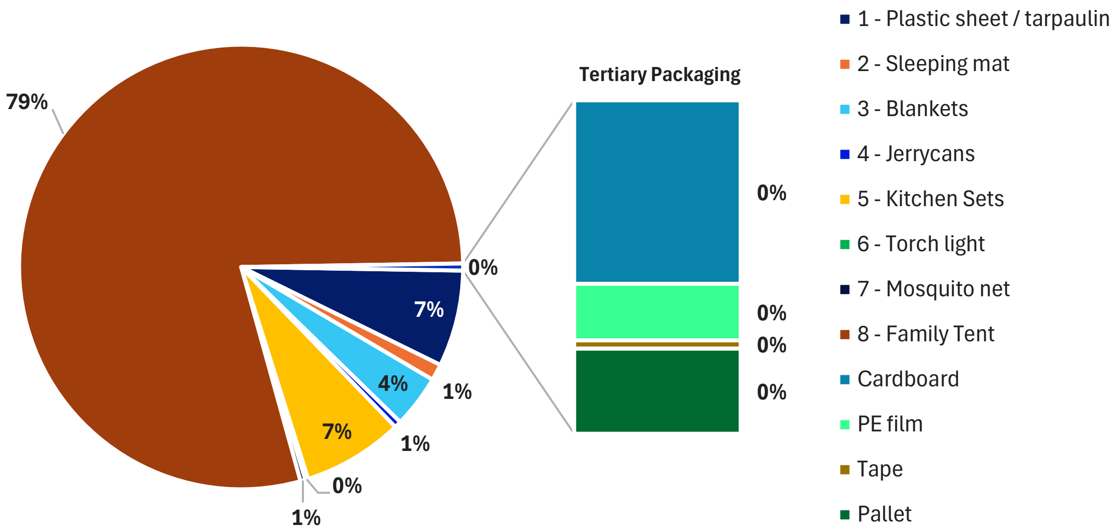


Figure 16 Reference NFI Kit overall impact and profile

To better understand the distribution of impacts among the remaining items, Figure 17 excludes the family tent. When viewed independently, the kitchen set and plastic tarpaulin dominate the impacts, primarily due to their use of stainless steel and PVC-based materials, both of which involve energy-intensive production processes and limited end-of-life options in crisis settings.

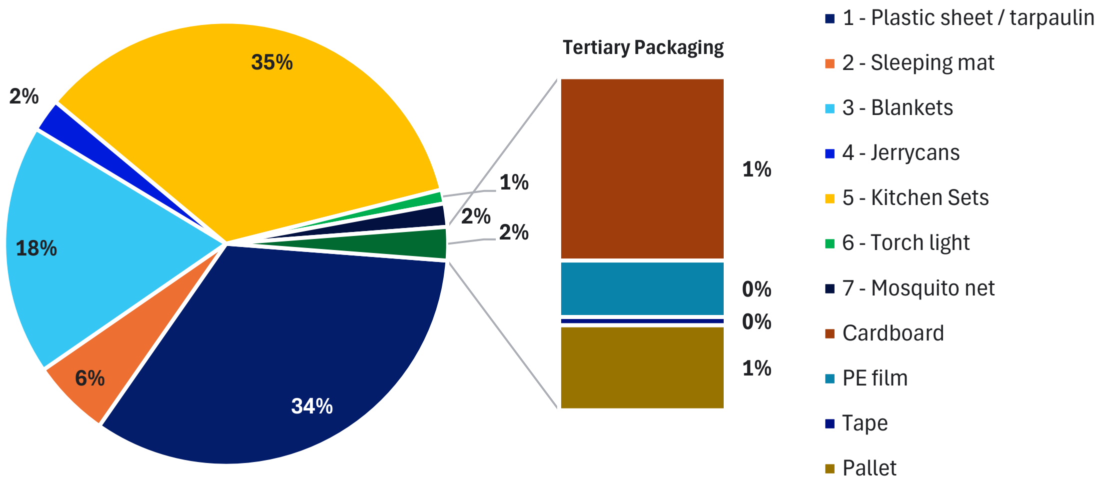


Figure 17 Existing NFI kit impacts, excluding the family tent

Figure 18 presents the changes in impacts when the reference items are replaced with the proposed bio-based solutions. Replacing the polyester mosquito net with a PLA-based alternative reduces impacts by approximately 23%, driven by lower fossil resource use and improved end-of-life performance. For the jerrycan, we also observe a reduction of around 13%, reflecting the lower climate change and fossil resource impacts of the PLA material compared with HDPE. Similar trends are seen for the tertiary packaging film and adhesive tape compared to the other kits.

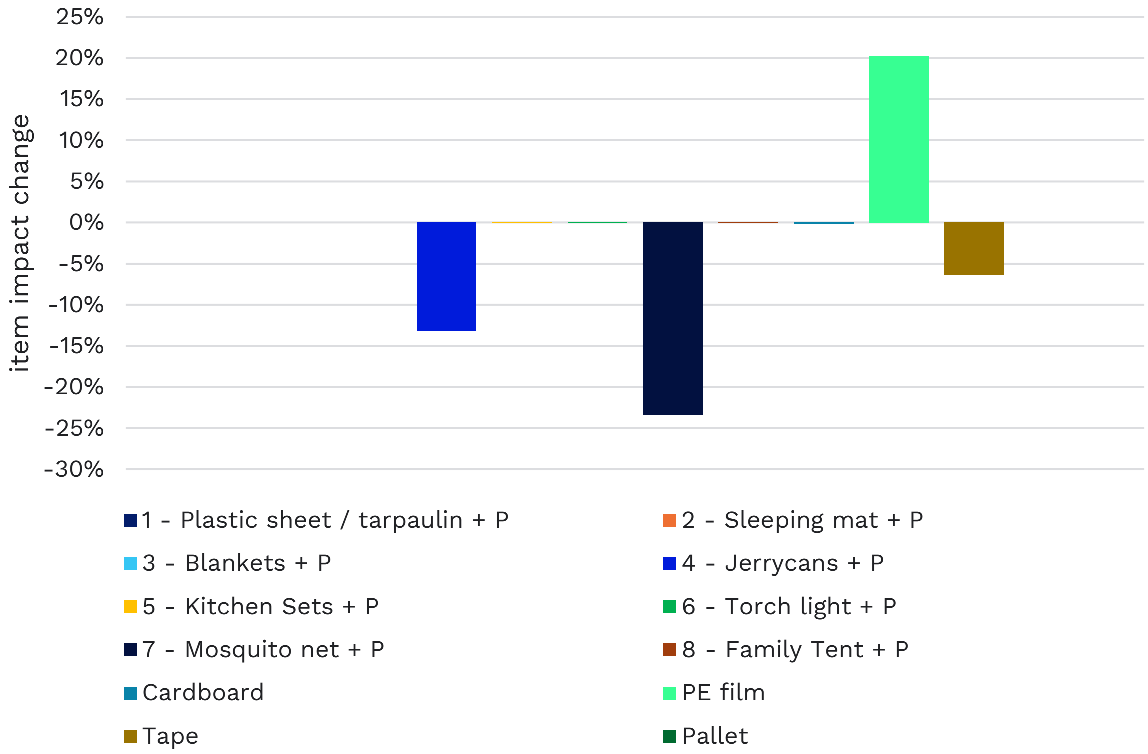


Figure 18 NFI Kit comparative impact change: substitution of references with solutions

Overall, the introduction of bio-based packaging and items has only a minimal effect on the NFI Kit, as the vast majority of impacts originate from heavy, durable household items that are not easily substituted with bio-based alternatives at the moment.

D. WASH Kit

Figure 19 presents the overall environmental impacts of the WASH Kit. The bar chart shows that the overall impact of this kit is much lower than that of the other kits by nearly an order of magnitude. The pie chart shows that the overall impacts are more evenly distributed among the items compared with the Agriculture, Food, and NFI kits.

The highest impacts are associated with the multipurpose cloth by 17% and reusable pad set by 15%, followed by both soap and the bucket each contributing 13%.

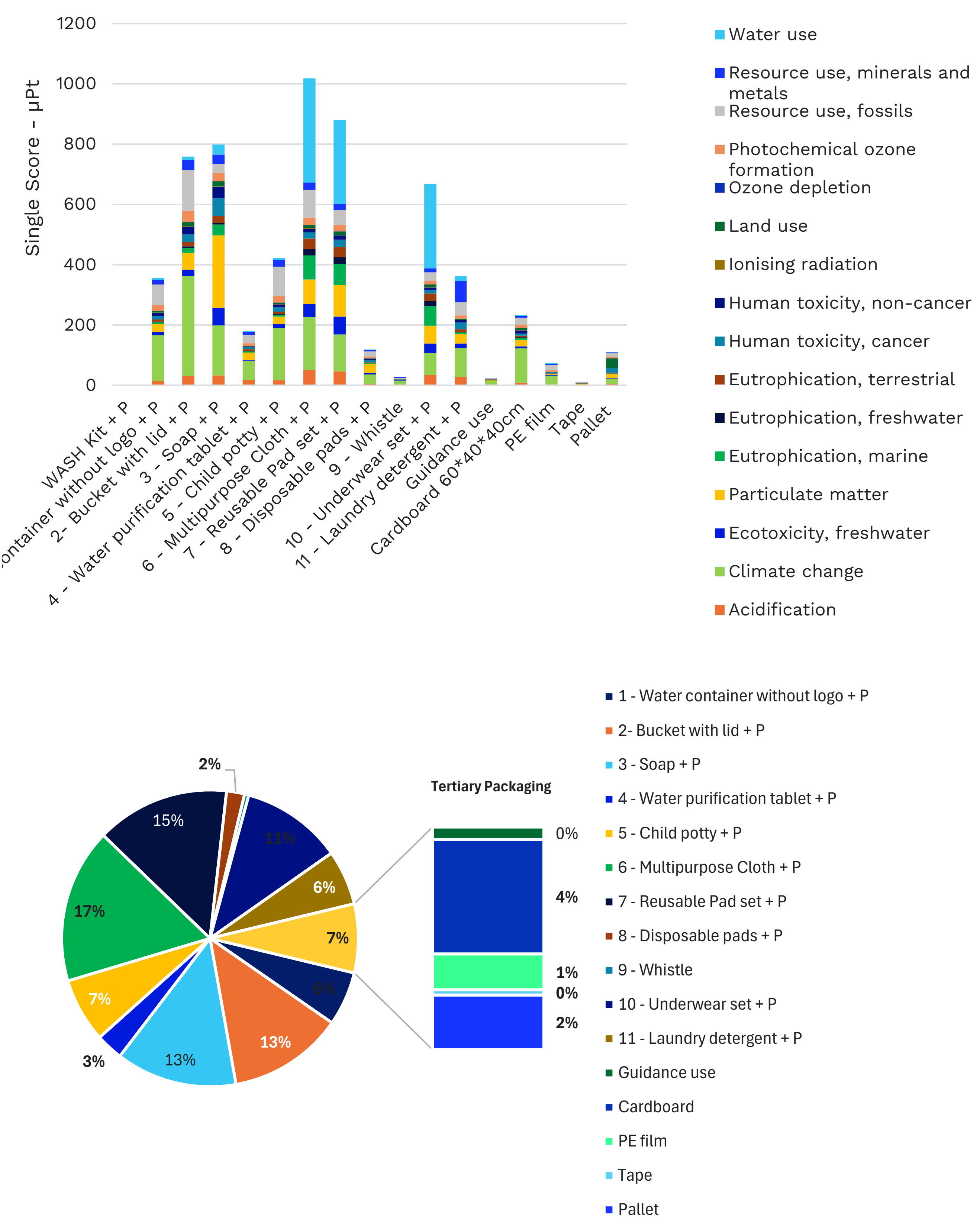


Figure 19 Existing WASH kit overall impact

When comparing the impacts of the WASH Kit with the solution items included versus the reference kit (Figure 20), the water container has its impacts increased by 45%, as mentioned before, due to the increase in PLA bottles. However, for the other items of multipurpose cloth, disposable pads and underwear sets, which hold a major part of the impacts together, as in Figure 18, their impacts decrease.

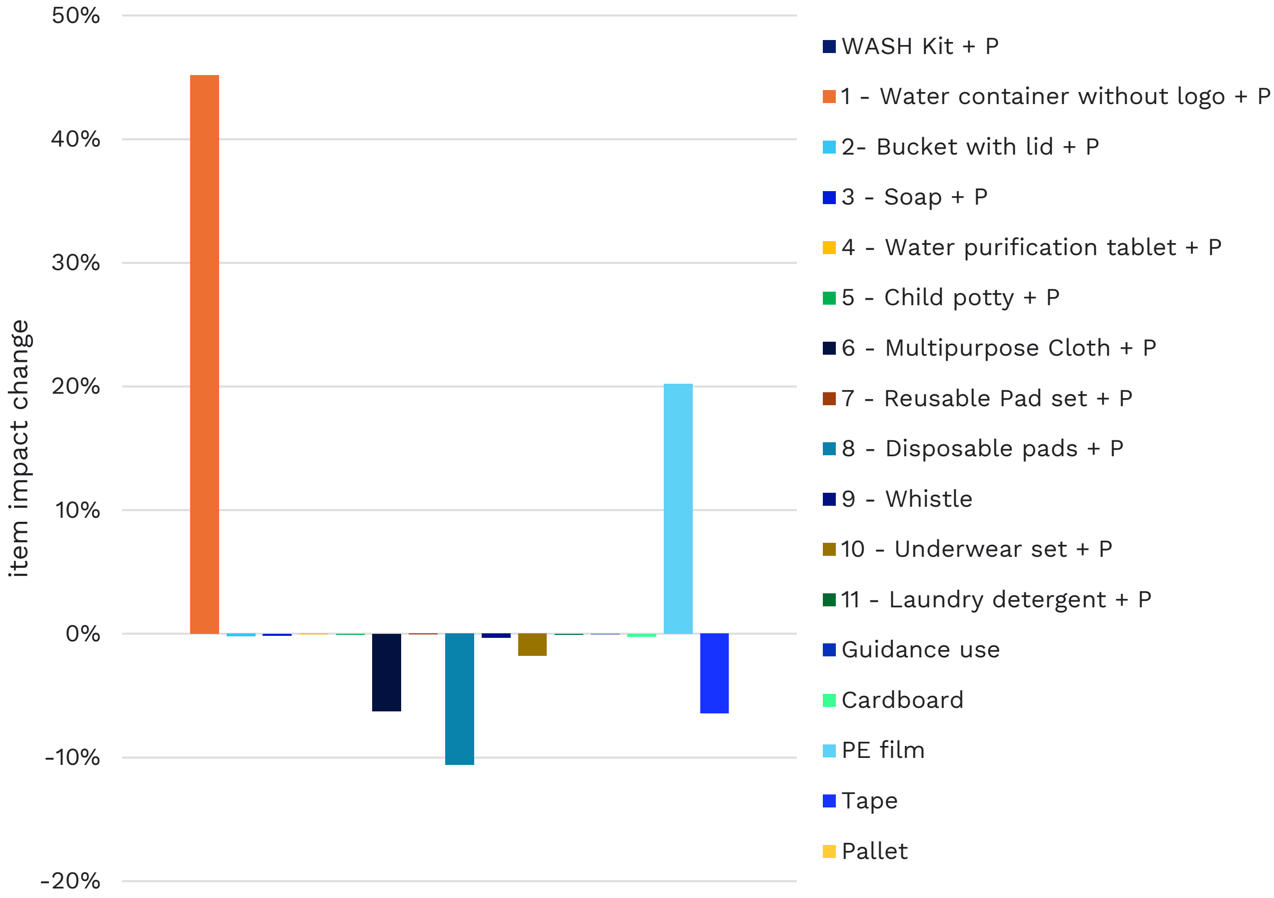


Figure 20 WASH Kit comparative impact change: substitution of references with solutions

Overall, the environmental gains from bio-based packaging in the WASH Kit are modest, but meaningful benefits arise from the reusability of certain items and from shifting away from petroleum-based materials.

V. Additional Indicators

The performance of kits in the additional indicators is compared in this section. For detailed item-to-item comparison please refer to the Figure 23 and Figure 24 in the Annexes (VII). In this section, only ecosystem quality and plastic effects on biota are addressed from D5.2, as the Material Durability Index did not provide meaningful insights for the products assessed, and biogenic carbon content is applicable only to bio-based materials, which would result in a one-sided comparison with fossil-based items.

A. Ecosystem Quality

As described in Deliverable 5.2, Ecosystem Quality (proposed by the ALIGNED EU project, from Impact World+) is an endpoint indicator that aggregates the effects of multiple impact pathways, including climate change, fisheries, freshwater transformation, and others, into a measure of potential damage to biodiversity. It displays how biodiversity can be affected by the fossil-based or bio-based materials.

By replacing the packaging and including the solution items, the difference displayed in Figure 21 is negligible since, in the overall impacts, effects of the solutions and bio-based plastics get diluted in the whole kit.

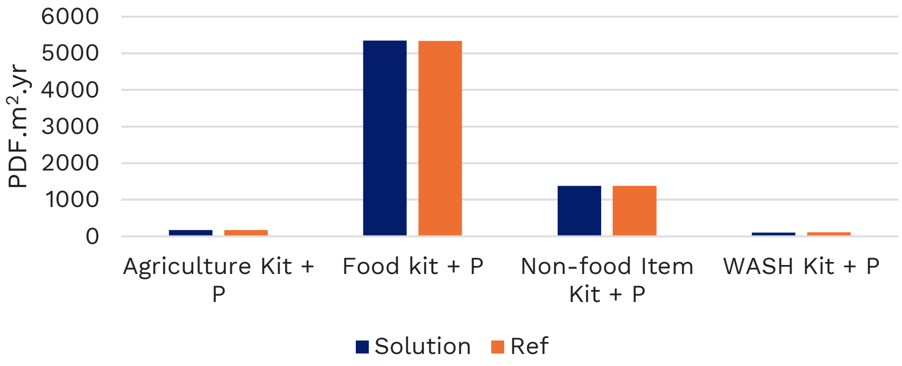


Figure 21 Ecosystem quality of the kits

B. Plastic Effect on Biota

The Plastic Effect on Biota (proposed by the CALIMERO EU project)) is an indicator calculated by Impact World+ v2.1 LCIA method. Depending on microplastic release in the environment, the methodology assesses impacts of plastic leakage on ecosystem quality in PDF.m².yr. Further details on this category are provided in D5.2.

Due to replacing fossil-based plastics with bio-based and biodegradable materials in the solutions, we see that the kits' impacts have been reduced. Figure 22 shows around a 12% and 13% reduction for the WASH and NFI Kits respectively and around 86% and 100% for the agriculture kit and food kit, respectively. This is because the majority of plastics used in those kits were in the packaging.

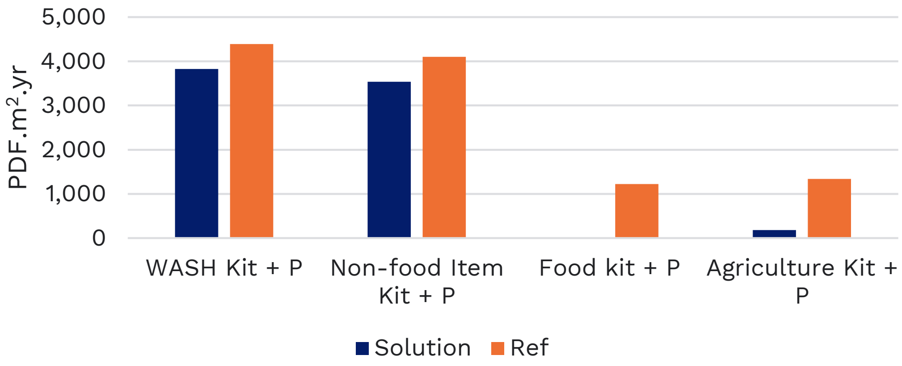


Figure 22 Plastic Effect on biota of the kits

VI. Conclusions and Recommendations

This deliverable assessed whether the bio-based materials identified in Bio4HUMAN deliver tangible environmental benefits when compared to the fossil-based reference items currently used in humanitarian operations. The results draw on harmonised functional units, the aligned inventories (D5.1), and the hotspot analyses (D5.2), enabling a consistent comparison across all four humanitarian kits.

Overall, the results indicate that bio-based solutions are not a universal substitute for conventional materials in humanitarian kits. However, the assessment shows that targeted, context-specific bio-based substitutions can deliver relative environmental benefits under current humanitarian waste-management conditions, particularly for lightweight items with high leakage potential and for impact categories related to fossil resource use and plastic effects on biota. These findings suggest that bio-based materials are best considered as incremental improvements, rather than as system-wide solutions.

In addition, the adoption of bio-based materials can contribute to a longer-term learning process for both humanitarian actors and affected communities. Even where waste-management infrastructure is not yet fully developed, behavioural change (such as waste segregation or more conscious consumption practices) takes time to emerge. Introducing bio-based solutions can therefore play a role in supporting gradual shifts in awareness and practices, helping to prepare the ground for future improvements in waste management and environmental performance.

Below, the key conclusions and actionable recommendations are summarised. For a roadmap that provides more specific actions across all kits and outlines steps that can be implemented in the short, medium, and long term please refer to D5.3 – Annex.

A. End-of-life (EoL) is a decisive factor in reducing particulate matter and toxicity impacts

EoL conditions strongly influence environmental outcomes. Open dumping and open burning, which are common in humanitarian settings, drive major impacts on particulate matter formation, human toxicity, and biodiversity damage (including plastic effects on biota).

While bio-based materials generally offer lower EoL impacts, these benefits are fully realised when suitable disposal routes are available. Many bio-based materials (e.g., PLA) require industrial composting or require a home compost environment (e.g., biodegradable tape). Without appropriate waste management, their potential advantages are still interesting but significantly reduced. Indeed, most of the identified solutions are biodegradable under specific composting conditions and could not naturally degrade if scattered in nature. Also, if they are treated through actual scenarios, the impacts on the environment at EoL will be almost as important as what is currently occurring with fossil-based non-biodegradable plastics.

Improving EoL management should therefore be treated as a priority intervention if the focus is on reducing waste and related health and environmental impacts. Recommended actions for HOs include:

- Encourage controlled disposal practices whereas feasible.
- Promote segregation of biodegradable vs. non-biodegradable waste.
- Support community-level systems for managing sanitary waste and mixed waste streams.
- Partner with local actors to establish managed disposal or treatment options, which rarely exists in humanitarian settings.
- Provide clear disposal instructions within kits, enabling proper handling by beneficiaries.

These actions help ensure more effective EoL management, reducing the impacts associated with open dumping, particularly toxicity, particulate matter emissions, and biodiversity damage caused by plastic leakage.

B. Bio-based packaging provides value only when functional performance is equivalent

Bio-based packaging (e.g., PLA bags, compostable laminates, PLA bottles) performs well for small and lightweight items but becomes environmentally unfavourable when additional units are required (such as 50 PLA bags replacing 1 HDPE bag), when higher total mass is needed (e.g., PLA bottles vs. LDPE jerrycan), or when mechanical strength is insufficient for bulk loads. In these cases, material inefficiencies outweigh the environmental benefits associated with bio-based feedstocks.

Recommended actions for HOs and suppliers:

- Encourage suppliers to improve the strength, capacity, and barrier properties of bio-based packaging. This will reduce the number of packaging units needed and ensure functional performance equivalent to fossil-based options.
- Use compostable bio-based packaging primarily for small-volume applications, where functionality is not compromised, and environmental benefits are more evident.
- Evaluate mechanical performance before integrating bio-solutions in large or heavy items.

These actions will help minimise the increased impacts observed when additional units of bio-based packaging are required due to current performance limitations. An analysis of ethical aspects of introducing bio-based materials within the HA sector is available in Annex (VII.B).

C. Impact drivers differ between kits

Across all kits, the environmental footprint is driven primarily by the core contents, not the packaging. In most cases, the tertiary packaging accounts for less than 5% of total kit-level impacts.

The main impact drivers for each kit are:

- Agriculture Kit: fertiliser and seeds (more than 70% of impacts)
- Food Kit: flour and rice (around 55% of impacts)
- NFI Kit: family tent (around 80% of impacts)
- WASH Kit: the impacts are more evenly distributed, but items themselves remain the main contributors.

This means that changing tertiary packaging alone cannot significantly reduce the overall kit-level environmental footprint. But changing primary, secondary and tertiary will reduce the EoL impacts of the kits and the plastic's effects on biota in the designated countries, which will make a difference.

Therefore, if the objective is to reduce overall impacts, the largest levers to optimise procurement should be prioritised. Recommended actions for humanitarian organisations (HOs) include:

- Prioritise procurement optimisation for the highest-impact items, such as fertilisers and seeds in the Agriculture Kit, flour and rice in the Food Kit, and tents in the NFI Kit.

- Treat packaging substitutions as a secondary measure, to be pursued after the main impact drivers within each kit have been addressed.

Focusing on these core items allows for the greatest reduction in overall environmental impacts.

VII. Annexes

A. Complementary figures and tables

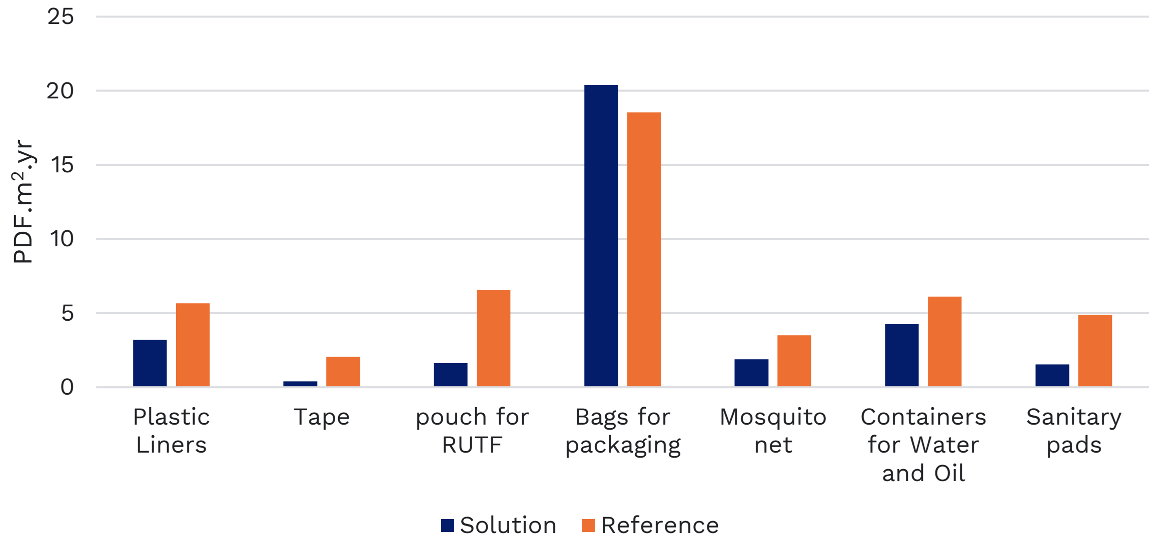


Figure 23 Ecosystem quality comparison of reference items and their solution replacement

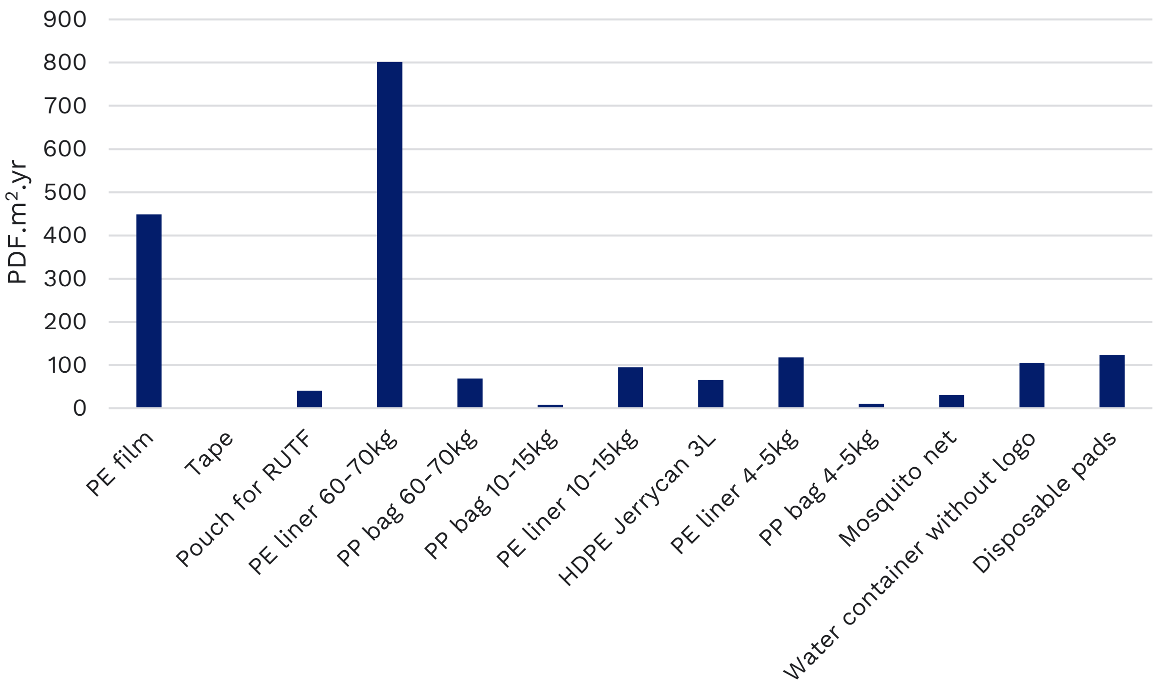


Figure 24 Plastic Effect on Biota for reference items being replaced. The solutions being considered composted at their end of life were considered to have zero impacts.

Table 2 Reusable Sanitary pad set (5 pads) with wings inventory[7]

Step	Material	Quantity	Material dataset
Production	Pads (80%): Absorbent core (cotton 55%)	0.132 kg	Fibre, cotton {RoW}| fibre production, cotton, ginning | Cut-off, U
	Pads (80%): Bottom layer (cotton 35%), Barrier liner (10%)	0.084 kg	Textile, woven cotton {GLO}| market for textile, woven cotton | Cut-off, U
	Pads (80%): Barrier liner (10%)	0.024 kg	Styrene-acrylonitrile copolymer {GLO}| market for styrene-acrylonitrile copolymer | Cut-off, U
Packaging	Primary Packaging (Cardboard 20*15*8 cm)	0.243 g	Corrugated board box {RoW}| market for corrugated board box | Cut-off, U
		1.53 g	PVC tape (not include in Ecoinvent 3.10)
Use	600 times of washing	4.5 g * 600	Soap {RoW}| soap production | Cut-off, U
		1 L * 600	Tap water {GLO}| market group for tap water | Cut-off, U

[7] **Calculations for number of pads**: Fourcassier, S. *et al.* (2022) 'Menstrual products: A comparable life cycle assessment', *Cleaner Environmental Systems*, 7, p. 100096. doi:10.1016/j.cesys.2022.100096.
Calculation for washing: Eco Femme (2025a) *How to wash my cloth pad? (part 1: A washing routine)*, *Eco Femme*. Available at: https://ecofemme.org/how-to-wash-cloth-pads-part-1/ (Accessed: 01 December 2025).
UNFPA East and Southern Africa Regional Office & Africa Coalition on Menstrual Health. (2025). *Water, sanitation and hygiene and waste disposal: Technical brief*. UNFPA ESARO. https://esaro.unfpa.org/sites/default/files/pub-pdf/2025-03/09%20-%20Sanitation%20and%20Hygieneand%20Waste%20Disposal.pdf

B. Ethics and Implementation Risks

The adoption of bio-based materials and packaging within humanitarian operations involves several ethical considerations and implementation risks that must be acknowledged to ensure responsible decision-making and avoid unintended consequences. While the environmental assessments presented in this deliverable highlight potential benefits, the transition to bio-based solutions must account for broader social, operational, and contextual factors.

1. Ethical Considerations

Avoiding Competition with Local Food Systems

Many bio-based materials rely on agricultural feedstocks (e.g., maize for PLA, cotton for sanitary pads, and packaging). Large-scale demand could, in certain contexts, place pressure on land, water, energy, or local food markets. Humanitarian organisations (HOs) should therefore ensure that procurement does not unintentionally compete with local food security or drive land-use change in vulnerable regions. A market analysis by studying the region's data on production, importation, or exportation volume of the necessary biotic resources would be necessary before implementing bio-based plastic production locally.

Equity and Acceptability for Beneficiaries

Bio-based items, particularly reusable products (e.g., sanitary pads), must respect cultural norms, gender sensitivities, and user preferences. Ethical deployment requires:

- ensuring that products are safe and appropriate for the intended context,
- supporting user dignity, privacy, and cultural acceptability, and
- avoiding placing additional burdens on beneficiaries (e.g., requiring access to clean water or additional energy sources for washing reusable items).

Transparency in Environmental Claims

As bio-based materials often carry sustainability labels or "compostable" claims, HOs must avoid unintentionally misleading beneficiaries or local partners about their real disposal requirements. Transparent communication is necessary to uphold accountability and trust, and dialogue with the solution suppliers also could enhance transparency throughout the supply chain.

2. Implementation Risks

Dependence on Specific End-of-Life (EoL) Conditions

Several bio-based materials evaluated in this deliverable (PLA, compostable laminates, bio-adhesives) achieve low impacts only when industrial composting or controlled disposal is available—conditions rarely met in crisis settings. If appropriate EoL pathways are not ensured, the environmental benefits may not materialise, and in some cases, impacts may increase. In this scenario, direct impacts of the product at end-of-life (plastic debris scattering) will be similar than the current situation.

Technical Performance Risks

Some bio-based materials currently face limitations in mechanical strength, durability, or barrier performance (e.g., PLA bags for heavy loads). If performance is insufficient, risks include:

- breakage during distribution,
- product loss or contamination,
- reduced beneficiary trust.

Field-testing and supplier quality assurance are therefore essential before large-scale deployment.

Operational and Supply Chain Risks

Introducing bio-based solutions may require new procurement channels, potentially increasing costs or creating supply dependencies. These risks include:

- limited global suppliers for specialised bio-based products,
- longer lead times,
- quality inconsistencies between production batches.

HOs should assess supply chain robustness and the potential need for diversified sourcing.

Regulatory and Certification Uncertainty

Humanitarian operations span multiple countries with varying regulations on compostable plastics, import restrictions, storage conditions, or safety standards. Compliance risks may arise if materials classified as “biodegradable” or “compostable” are interpreted differently by national authorities.

3. Mitigation Strategies

To responsibly implement bio-based solutions, the following cross-cutting considerations are recommended:

- **Conduct field validation tests** for mechanical performance before adoption at scale.

- **Ensure transparent communication** on disposal requirements and limitations.
- **Assess local waste management capacity** to avoid misaligned EoL expectations.
- **Strengthen supplier due diligence**, ensuring material origins do not compromise food security or ecosystems.
- **Integrate gender- and culture-sensitive design and distribution practices** when (re-)introducing reusable or personal-care items.

Develop risk-aware procurement strategies, including alternative suppliers and contingency planning.

To conclude, bio-based solutions offer promising environmental benefits but must be implemented with care to ensure they do not create new environmental, social, or operational risks. Ethical considerations, particularly around food system competition, cultural appropriateness, and transparency, are essential to ensure that sustainable materials also support fair, safe, and dignified humanitarian assistance. A risk-informed and context-sensitive approach will maximise the positive impact of the Bio4HUMAN innovations.