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Bio-based solutions in the context of humanitarian aid to reduce environmental impact of SWM at local level

Bio4HUMAN



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List of abbreviations

Abbreviation	Full name/Meaning
AD	Anaerobic Digestion
BSF	Black Soldier Fly
CBE JU	Circular Bio-based Europe Joint Undertaking
DRC	Democratic Republic of Congo
EF3.1	Environmental Footprint 3.1
FGD	Focus Group Discussion
HA	Humanitarian Action
HO	Humanitarian Organization
HSC	Humanitarian Supply Chain
HDPE	High-Density Polyethylene
IDP	Internally Displaced People
KII	Key Informant Interview
LCA	Life Cycle Assessment
LDPE	Low-Density Polyethylene
MDI	Material Durability Indicator
NGO	Non-Governmental Organization
PDF·m ² ·yr ⁻¹	Potentially Disappeared Fraction per m ² per year
PLA	Polylactic Acid
PBAT	Polybutylene Adipate Terephthalate
PP	Polypropylene
PET	Polyethylene Terephthalate
PVC	Polyvinyl Chloride
SS	South Sudan
SMW	Solid Waste Management
WFP	World Food Programme



1. Bio4HUMAN introduction

Bio4HUMAN Project (Identifying BIO-based solutions FOR waste management applicable to HUMANitarian sector), is a pivotal Horizon Europe-funded project aimed at developing a roadmap to address solid waste management (SWM) challenges in humanitarian settings. Bio4HUMAN started in January 2024 and will last until June 30, 2026. The main outputs of this project will be:

- A list of approximately 10 innovative bio-based products and technologies assessed through Life Cycle Assessment (LCA). These solutions are intended to address SWM challenges in two distinct humanitarian contexts: Democratic Republic of Congo (DRC) and South Sudan (SS).
- The “easy to handle” practical tools for socio-economic and governance aspects evaluation of bio-based solutions.
- A set of guidelines, recommendations on environmental, economic and social aspects for SWM to be used by policymakers, bio-based sector actors, humanitarian aid practitioners, and the scientific community for scale-up and replication purposes.

1.1 Deep insight into the project

Solid waste is a concern in any human settlement and is generated at household, institutional, or community levels, as it is intrinsically linked to human activity. In humanitarian contexts, effective SWM is critical to ensure safe handling during and after emergencies. However, once humanitarian waste enters the general waste streams in those settings it becomes indistinguishable from regular waste unless it is specifically marked [1]. Therefore, if not properly treated, SWM in humanitarian settings poses significant environmental challenges due to limited resources and infrastructure, thereby contributing to surface pollution and ground water as much as soil and air, since much of this waste is non-biodegradable. Humanitarian operations generate a wide range of waste types, including organic matter, plastics, sanitation waste, construction debris, household waste, cardboard, and paper [1]. In this context, bio-based solutions and compostable materials offer a promising approach to addressing solid waste management challenges.

The Bio4HUMAN project [2], funded by the European Commission, aims to address these SWM challenges in humanitarian settings. Its main objective is to provide humanitarian aid operators and stakeholders in the bio-based sector with a comprehensive list of bio-based solutions for SWM, applicable across various humanitarian contexts. The project focuses on two specific contexts: South Sudan (SS) and the Democratic Republic of Congo (DRC).

To achieve this objective, five steps are applied: (1) Stakeholder analysis and SWM needs assessment in two locations, (2) Scoping exercise for bio-based solutions (products and technologies), (3) Life Cycle Assessment (LCA) of the identified solutions (4) Feasibility evaluation in DRC and SS and (5) Replication roadmap of solutions identified applicable to diverse humanitarian contexts.



1.2 Humanitarian sector needs assessment

The results of this needs assessment are included in Deliverable D3.3 Humanitarian Sector Needs Assessment report [1]; in this technical communication, a brief summary is included. The assessment was conducted by two Non-Governmental Organization (NGOs), People In Need (PIN) and Polish Humanitarian Action (PAH) that are part of the Bio4HUMAN consortium and have decades long lasting experience in Bio4HUMAN selected locations. The findings of this assessment focused on: types of waste present in humanitarian settings, SWM standards and sustainable models, as well as the current state of SWM in these settings. This assessment allowed Bio4HUMAN to identify the main challenges related to SWM in humanitarian settings, opportunities and the potential use of bio-based solutions.

Bio4HUMAN focuses on solid waste: any type of garbage, trash, refuse or discarded material (end-of life products) [3]. Bio4HUMAN targets two countries in Sub-Saharan Africa – the DRC and SS, both considered as protracted crisis, and characterized by recurrent natural disasters and/or conflict, longevity of food crises, breakdown of livelihoods, and insufficient institutional capacity to react to the crises [4]. While we can describe humanitarian waste (such as its source and packaging details), it is not possible to differentiate it from the general waste generated in humanitarian settings unless it is specifically marked as humanitarian waste (e.g., World Food Programme (WFP) branded flour bags). After humanitarian waste enters the waste stream and decays, it blends indistinguishably with general waste.

Primary data on SWM practices in SS and DRC was collected in three ways¹: a) quantitative survey with International Humanitarian Organization (HOs) based in Europe, and in the DRC and SS and National HOs from the DRC and SS, b) qualitative keys and Focus Group Discussion (FGD) with representatives of 5 stakeholder groups (DRC, SS, global), and c) solid waste observations in the DRC and SS. Secondary data were collected through conducting literature reviews.

Humanitarian and general solid waste in DRC and SS

Most needs assessment respondents found it difficult to distinguish between humanitarian and general waste, as all of them end up mixed together in the same places once they enter the waste stream and start to decay. The only research environments where some distinctions could be made were Internally Displaced People (IDP) camps and health facilities, as these are settings with limited sources of waste where humanitarian actors usually distribute items, which fill the usual supply gaps and as such can thus be distinguished, at designated spaces.

Based on the qualitative Key Informant Interviews (KIs), Focus Group Discussions (FGD) as well as observations, the type of waste (both humanitarian and general waste) that is found to be most

¹ <https://www.kobotoolbox.org/> used as data collection tool



ubiquitous in all four environments – camp, rural, semi-urban, urban – is primarily plastic waste, especially plastic sachets and bottles, followed by organic waste from humanitarian distributions, fields, gardens, and markets. Metal (tins, cans, car parts, needles, razors), cartons, paper and medical waste are present but in comparatively lesser amounts than plastic and organic waste. The least cited and observed type of waste was glass and textile in all researched settings.

Solid Waste Management in Humanitarian Settings

Humanitarian assistance is provided to affected countries and communities where the existing SWM systems are broken or overloaded while receiving more or new types of waste. Existing systems are owned by the host communities and only partly operational; for example, regular waste collection is impossible because roads or paths are blocked, or access is not possible due to conflict [5]. The disaster/humanitarian waste adds to the already present unmanaged waste [6], left for local authorities and communities who lack proper SWM infrastructure and equipment, to deal with it. The accumulated waste that often remains in communities or is disposed inappropriately causes considerable adverse impacts on the environment, public health, and climate. The following risks associated to waste were identified by DRC and SS respondents:

- **Public health.** The biggest concern associated with improper SWM included illnesses and injuries that affect adults but also children who were said and observed to play with and in waste as well as pick waste to later sell it. People can also contract diseases from contaminated water, which had been in contact with waste either on the ground or deposited in water channels, which is a common SWM practice in the case study areas. Another common local SWM practice – re-use of deposited plastic bottles for milk, juice and alcohol, and sachets – can be a source of disease. Also, the burning of solid waste can produce toxic fumes detrimental to health.
- **Environmental and livelihood.** The negative environmental impacts of bad SWM practices mentioned by respondents included pollution on water systems, land, atmosphere, and also affected to animals. However, these practices were often linked with people's livelihoods. The most often discussed environmental impact was contamination of water, which starts with waste being thrown into water channels and waste deposited on steep slopes transported into water ways by rainwater. Fishing, a common livelihood in the sampled areas, is also impacted because plastic and other waste affects fish in rivers and lakes. Another challenge is waste blocking hydroelectric dams, such as the Rusizi hydroelectric dam, which can affect electricity production and cause electricity cuts, impacting livelihoods.
- **Children's exposure:** Children's exposure to solid waste is highlighted as a separate topic because it was one of the major respondent's concerns in terms of risks associated with SWM, and children's exposure to solid waste was also observed on several occasions, especially in IDP camp settings but, overall, in all of the researched settings. Children are the most likely to contract diseases or injure themselves due to their frequent exposure and lack of understanding of the associated risks.
- **Conflict with neighbours:** One of the SWM challenges reported by the respondents was the impact on neighbour relations. When the waste stored on the ground and in water channels starts decomposing, the unpleasant smell increased mosquito presence. Furthermore, fumes



and smell caused by burning waste can also be a source of annoyance and even lead to conflicts.

While waste disposal systems in some Sub-Saharan African countries have been slowly improving, (primarily in cities, where efforts focus on constructing landfills, closing dumps, and formalizing collection systems to mitigate environmental and health impacts), 69% of waste is still predominantly openly dumped or burned. From the rest of the waste, 24% of it is disposed of in some form of a landfill and only about 7% is recycled or recovered [7]. In SS and the DRC, only a small fraction of households, businesses, and other organizations have their waste removed by waste collectors and transported to official or unofficial landfills. This is practiced only in urban areas where the needed road infrastructure and SWM services may be available and where there are individuals with financial means and environmental awareness. However, waste collection in densely populated urban areas may be hindered due to plots' accessibility and non-existence of roads, such as in case of Bukavu. Waste that is thrown away in own plots may be burned or, if organic, composted, while waste deposited in the streets and water channels often ends up in water ways, where the process is expedited during rainy season.

Solid waste management challenges identified in the DRC and SS

The following table, extracted from D3.3 of Bio4HUMAN [1] summarizes the challenges identified by PIN and PAH in the primary data collection in the DRC and SS.

Due to the risks mentioned above, and the challenges with respect to SWM, HOs have been trying to find more green/sustainable alternatives to the plastic (petroleum-based plastics—also referred to as “conventional” or “virgin” plastic) and cardboard and paper packaging for relief items. This substitution of conventional plastics by sustainable packaging, together with other opportunities such as, waste prevention, reuse and recycling, waste-to-energy, waste-to-resource, safe and accessible disposal sites and data and digitalization to strengthen the waste management value chain; can make a significant difference in addressing the SWM challenge



Table 1. SWM challenges in DRC and SS identified in D3.3 OF Bio4HUMAN project

Source: Deliverable 3.3 Humanitarian sector needs assessment report (Bio4HUMAN)

Challenge	Description
Lack of (official) SWM infrastructure and services	This issue starts at the household level with the lack of bins, and continues with public infrastructure, which lacks public bins, sufficient number of good quality waste collection trucks, and safe landfills. The number and capacities of official waste collecting businesses is insufficient, while official and registered waste transformation businesses are either small enterprises that use simple or even artisanal techniques or are completely absent
Lack of financial resources and poverty	The government lacks resources to provide services, while businesses do not have funding to expand, industrialize and improve the quality of their services, as there is lack of financing options and opportunities.
Lack of (enforcement of) SWM national policies	In DRC, the SWM legislation is in place; however, it is not followed by sufficiently active enforcement from the government's side, including through imposition of sanctions for failure to comply. On the other hand, South Sudanese SWM legislation has not been completed and approved.
Lack of strategic planning for SWM	In both countries, there is a lack of proper planning for SWM at national and local levels. Moreover, HOs have not until now considered proper planning for their SWM during humanitarian interventions.
Limited coordination among SWM actors	The existing SWM service providers tend to work in silos. For example, some of the waste transformers also arrange for their waste collection themselves, whereas systematic cooperation with waste collectors could be established.
Lack of prioritization, capacities and policies of HOs for implementation of sustainable SWM	The survey conducted with HOs as well as the KIIs show that many humanitarian and development organizations active in humanitarian settings, such as DRC and SS, do not have any or approved policies or guidelines regulating SWM in their operations and procurement.
Lack of quality waste data and monitoring	Monitoring of and having quantitative data on waste and its management is a big challenge for all stakeholders –government, HOs, businesses and academia.
Technical barriers	Generally, there is a lack of technical experts that could plan and implement good SWM practices in both the government, academia, HOs, businesses, health facilities and communities.
Lack of SWM awareness	Awareness and general knowledge of good SWM practices and their correct performance among general population is very low.
Mentality (low perception of responsibility)	The respondents noted a general lack of personal responsibility for how waste is managed. Community often refers to the responsibility of the government, while the willingness to personally contribute by keeping own surroundings clean and subscribing to waste collection is low.



Little involvement of academia

Universities and research institutes and laboratories are usually not much consulted or involved in SWM agenda by the government or by HOs

Armed conflict

The general security environment in both countries poses barriers to SWM activities, including transportation of waste to landfills or cross-border for waste transformation.



1.3 Gap analysis

The results of the gap analysis have been extracted from Bio4HUMAN's D4.2 Gap analysis report [8]. During the development of the project and the different analysis carried out, several SWM challenges were found due to data deficiencies, operational efficiency and limited technological adoption. Addressing these challenges requires a comprehensive approach that integrates environmental considerations into every stage of the supply chain, fosters collaboration across teams and sectors, and adapts solutions to the realities of humanitarian contexts. The current state can be characterized by the following:

Table 2. Current state of the gaps in SWM in Humanitarian Action (HA)

Source: Deliverable 4.2 Gap analysis report (Bio4HUMAN)

Challenges	Description
Limited data regarding SWM across supply chain stages	This lack of documentation suggests that SWM is not systematically monitored or prioritized, limiting the ability to develop evidence-based strategies for waste reduction and management.
Waste generated from logistics is crucial	There is a need for greater collaboration between needs identification and planning teams to mitigate downstream waste impacts.
Prioritization of aid delivery over sustainability	The operational efficiency over environmental responsibility reflects a broader HOs mindset, where waste management is seen as a secondary issue
Planning and Procurement challenges and opportunities	Planning and Procurement stages do not generate lots of waste itself but have critical influence on next stages. The early-stages decisions could have a crucial role in reducing overall amount of solid waste.
Technological and logistical gaps	There are number areas of HA interventions in which advanced technology and tools are being used. However, those tools along with bio-based solutions are not explored enough or used on a larger scale. It is followed by logistical challenges, including changing regulations and poor infrastructure, which impacts the effective waste management.

The gap analysis showed that the most critical gaps are related to "Insufficient financial resources" and "Lack of coordination among facilities". These gaps highlight their significant impact on operations due to limited resources, high financial dependency, and insufficient relationships between facilities throughout the supply chain. Following is "Weak policy framework and reinforcement" which highlights coordination challenges and the need to involve local governments and institutions to strengthen policy alignment and enforcement.

The desired state of SWM in Humanitarian Supply Chain (HSC) is a holistic, sustainable ecosystem where waste is minimized, resources are reused, and environmental impacts are mitigated across all stages. It addresses current shortcomings through eco-design, infrastructure, advanced technologies, stakeholder collaboration, and sufficient funding. By integrating best practices and innovative bio-based solutions, this vision aligns humanitarian objectives with environmental



security, ensuring aid delivery enhances rather than degrades the ecosystems of crisis-affected regions.

2. Bio-based solutions

The actual process of scoping for bio-based solutions took the form of surveying Bio-based Industries Consortium (BIC)² entities (members and associate members) and analysing various data sets, incl. a) outcomes of projects financed by the Circular Bio-based Europe Joint Undertaking (CBE JU) initiative, b) the lists compiled by national and international organisations advocating for the bio-based solutions, c) the patents d) the awards given to the exceptional bio-based products and technologies. The results of this scoping of the solutions have been extracted from D4.1 List of bio-based solutions [9].

After initial analysis, thirty-two bio-based products and technologies were selected and put up to the internal and external consultations. The internal observations referred mainly to the possibility of the local production (i.e. in the humanitarian destination) of the proposed products, the quality, the actual demand from the humanitarian organisations, the “end of life” scenario (in particular the feature of biodegradability), price and cost considerations, the local resources needed for the implementation of technologies and the functional and operational elements. The successfully conducted internal and external consultation processes gave rise to establishing the final list of twenty-seven bio-based products and technologies. The solutions on the list are divided into six clusters:

1. Multi-purpose packaging products,
2. Packaging products for food and drinks,
3. Hygiene products,
4. Construction related products,
5. Other products potentially applicable in the context of humanitarian interventions,
6. Small-scale technologies.

The list is comprised of solutions contributing strongly to a more circular bioeconomy and exercising features of renewability, recyclability, biodegradability, compostability and sustainability. There are bio-based solutions with proper functional properties, comparable with fossil-based counterparts. The presented solutions have been appraised by the Project’s Ethics Advisory Board and Internal Ethics Officer as relevant for the context and the purposes of Bio4HUMAN during a separate working meeting. In general, these six clusters can be grouped into the following:

²The Biobased Industries Consortium (BIC) is a European association focused on promoting sustainable and competitive bio-based industries through innovation and collaboration. BIC consortium supports the project in various activities and signed support to the project (LoS).



- ❖ **Bio-based products derived from biological origin.** These materials have the potential to replace plastic fossil-based materials for flexible packaging applications or replacing other materials and humanitarian aid items like hygienic items or insulation materials, and
- ❖ **Technologies allowing for the transformation of local organic waste** into high-protein animal feed, organic fertilizers, or biogas.

The information related to the bio-based products and End of Life technologies has been extracted from D4.1 The list of bio-based solutions relevant to waste management in the humanitarian context [9] and D5.1 Data collection from partners: state-of-the art and innovative solutions [10].

2.1 Bio-based products

Based on inputs from NGOs (PIN and PAH), four types of humanitarian aid kits were identified: food, WASH (Water, Sanitation and Hygiene), agricultural, and Non-Food item (NFI) kits. In the reference scenario these kits are mostly made with fossil-based materials. The bio-based materials will be evaluated to assess the potential to be incorporated in the kits such as biodegradable films, compostable pouches or Polylactic acid (PLA) containers. The main goals in Bio4HUMAN are:

- To assess and compare the environmental impact of innovative bio-based solutions against current practices in the context of SWM in humanitarian settings. This comparison is made by defining sustainable scenarios that consider the environmental benefits associated with the integration of bio-based solutions. This comparison will use Life Cycle Assessment methodologies to measure, environmental, cost and social impact of the solutions.
- To reduce solid waste by the incorporation of bio-based products and technologies in humanitarian context.

Below is a summary of the innovative bio-based solutions [3], classified by different functionalities, which are assessed in LCA (see section 3):

1. Multipurpose packaging products. These solutions are designed to provide fastening or protective functions for all the kits:

- Mycelium protective material consists of a combination of protective mailers made from mycelium and waste from the woodworking or agricultural industry. It is a 100% biodegradable material according to ASTM D5988-18.
- Adhesive tape: made from about 90% renewable resources, featuring a bio-based PLA film and natural rubber adhesive. Suitable for sealing biodegradable bags, films, and sustainable packaging, as well as medium to heavy cardboard boxes and manual dispensers. Certified as home compostable and biodegradable.
- Biodegradable laminating film: a 100% biodegradable film made from renewable resources like corn. Certified 100% industrial compostable.

2. Food and drinks packaging products. The products are intended to substitute primary packaging items from the Food basket.



- PLA bottle for water or for oil consists of 100% plant-based water bottles made from sugar cane and non-GMO materials, including the cap and label. The bottles are industrially compostable. In this sense, PLA, one of the most used bioplastics worldwide, is based on the polymerisation of lactic acid, which is synthesised from glucose. It can be derived from maize, sugarcane and biowaste.
- Compostable Pouch for RUTF: made from PLA, cellulose metallized and cellophane. This compostable pouch can be used to contain Ready-to-Use Therapeutic food (RUTF). This solution is fully biodegradable and home compostable.

3. Hygiene products: from the WASH kit.

- Sanitary pads: made from jute, bagasse, banana fibre, and water hyacinth, using agricultural plant waste materials. They are 100% home compostable and certified.

4. Construction related products (with potential for replicability in other humanitarian setting, e.g. Ukraine):

- Foams for insulation made with 65-75% renewable material and recyclable.
- Wool Insulation material: consists of 100% natural sheep wool insulation that is renewable. It is reusable and biodegradable.
- Hemp: bio-based insulation made from hemp, a fast-growing material, with high bio-based content and thermal performance. It is reusable and recyclable.

5. Other products potentially applicable in the context of humanitarian interventions

- Disposable bag: made from renewable sources that can be disposed of with organic waste. DIN EN 13432 Compostable certified.
- Monofilaments fishing nets/mosquito nets use bioplastic (PLA) formulations. They are biodegradable.

2.2 End of life solutions: Small scale technologies

In addition to bio-based product solutions, small-scale technological solutions for management of biowaste have been explored to further reduce the amount of waste destined for landfills or open dumping sites. These technologies are based on anaerobic digestion (AD) and bioconversion using the Black soldier fly (BSF). By transforming biowaste into useful co-products, including biogas, compost, and animal feed in the case of BSF, these methods not only help mitigate environmental impacts but also contribute to circular economy principles. Moreover, they present promising end of life solution treatment opportunities for biodegradable materials, ensuring that such products can be



reintegrated into the value chain in a sustainable manner. Anaerobic digestion of organic waste to produce biogas as a clean fuel for cooking and heating, or electricity generation. Anaerobic reactors are versatile to accept different types of organic waste, including fibrous agricultural waste, food waste, low-risk organic waste, kitchen, garden residues, and animal or domestic manure. In WP4, four specific innovative AD reactor solutions were selected described as: Modular renewable AD, single stage biogas digester, micro biogas digesters and domestic biogas technologies. The differences between the four reactor types lie mainly in the type of waste treated (fibrous, non-fibrous), the temperature they are running at (influencing the amount of inoculum and the generation of mesophilic or thermophilic bacteria, and the energy consumption requirements), water content (influencing the obtention of liquid digestate or the conditions of the reaction, and all those factors will have an effect on the efficiency of biogas production and the emissions to air. There are differences in scale (processing capacity) which depend on the amount of waste to be treated [3], but this project has focused on the small-scale technologies to seek for the easiest implementation in the humanitarian contexts under study.

Black Soldier Fly (BSF) technology utilizes the larvae of the Black Soldier Fly to efficiently decompose and recycle organic waste materials. These larvae consume a wide variety of biodegradable waste, transforming it into valuable biomass rich in protein and essential nutrients. The harvested larvae are processed into high-quality animal feed, serving as a sustainable alternative to traditional feed sources like fishmeal and soy. Additionally, the residue left after larvae processing acts as a nutrient-dense organic fertilizer that enriches soil health and boosts crop productivity. The BSF technology significantly reduces environmental pollution and greenhouse gas emissions. Overall, it represents an innovative, circular solution that supports eco-friendly waste management and sustainable agriculture. In Bio4HUMAN project, the two BSF technologies, which differ only in scale, are:

- ❖ The Small-Scale Residue Utilization Pathways (SSRUP) – BSF technology originates from a project primarily funded by the European Union and has been implemented in several African countries [3], [11].
- ❖ And Black soldier fly (BSF) opportunities come from ACEN Foundation and EAWAG [12].

The small-scale technologies may provide a solution for end-of-life treatment of organic waste, since five different systems have been selected, that could fit a specific humanitarian setting. Eventually, once the type of organic waste generated from each of the biobased products in Section 2.1 is defined, it could be directed as well to the correct small-scale technology screened here.



3. Environmental impacts mitigation of the solutions

The information included in this section has been extracted from Bio4HUMAN's D5.2-Hotspot analysis of the current and innovative solutions [13], by WeLOOP. In this report the results of the different materials analysed are included; however, the LCA of all bio-based solutions will be presented in D5.3-Identification of the best available innovative solutions based on LCA [14].

3.1 Environmental indicators selection

To perform a hotspot analysis of the solutions identified in the project, the impacts were calculated with LCIA methodologies using SimaPro LCA software. The processes were modelled during T5.1 with the Ecoinvent 3.10 database and literature reviews. To perform the necessary work 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 international impact assessment methodologies (e.g., Impact World+, Environmental Footprint (EF) 3.1), hotspots analyses were performed for 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 impact from manufacturing to EoL stage, given that the aim of the project is to reduce these impacts. For the EoL of the solutions in D5.2 [14], Ecoinvent database processes for anaerobic digestion or composting, have been taking into account for the first LCA of the materials. The EoL of the technologies identified in section 2.2 will be analysed in D5.3 [15]. 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/benefit 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 with 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.

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 health³. By structuring the assessment into distinct categories, EF3.1 ensures consistency, comparability, and transparency in environmental evaluations across different sectors and applications. Some were selected as most relevant for the Bio4HUMAN project locations based on their relevance to fossil and biotic resources:

Table 3. Environmental impact categories from EF3.1 method analysed within Bio4HUMAN

Source: Deliverable 5.2 Hotspot analysis of the current and innovative solutions (Bio4HUMAN)

Environmental impact category	Unit	Short description
Climate change	kg CO ₂ eq	Represents the global warming potential associated to greenhouse gas emissions (fossil, biogenic and land use).
Water use	m ³ - world equivalents	Reflects on the deprivation of freshwater caused by the process
Resource use, fossils	MJ	Evaluates the amount of fossils resource use, converted into megajoules, fossil fuels having inherent energy.
Land use	Pts	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
Ecotoxicity, freshwater	CTuE	Evaluates the direct impacts of toxic substances on freshwater ecosystems like rivers, groundwater reserves etc.
Eutrophication, freshwater	kg N eq	Pauses the issues relative to overfertilization of freshwater resulting in ecosystem balance disruption with plant or algae overgrowth, suffocating the surrounding wildlife.

Apart from the indicators of EF3.1 method, additional indicators were selected based on a review of fellow EU project indicators relevant to Bio4HUMAN:

- **Biogenic carbon** (extracted from ALIGNED project [15] and EN15804 + A2 standard): represents the amount of CO₂ 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. This indicator is only studied for the solutions as 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.

³ Impacts on ecosystem and Human Health were taken from Impact World + method.



- **Plastic effects on biota** (from CALIMERO project [16] and Impact World +): is an indicator calculated by Impact World + v2.1 impact assessment methodology. Depending on microplastic release in the environment, the methodology assesses impacts of plastic leakage on ecosystem quality in PDF.m².yr (Potentially Disappeared Fraction of species, per m² per year).
- **Ecosystem quality** biota (from ALIGNED project and 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 [17] project from Mesa et al. (2020) [18]: 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.
- **Criticality (from CALIMERO project)**: 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 concerning factors such as high demand, then the criticality is even higher [19].

In the following section, the results are extracted preliminary results for 1 kg of bio-based materials (PLA) and 1 kg of reference materials: High-Density Polyethylene (HDPE) and Low-Density Polyethylene (LDPE).

3.2 Impact assessment of the bio-based materials: “Cradle-to-grave”

This hotspot analysis identified the impact categories contributing to 80% of the total impact, in single score results to show the overall environmental impact. Then, life cycle stages, processes, and elementary flows associated with these impact categories were identified. For the preliminary results of Bio4HUMAN [3], it was observed that some categories are more specific to fossil-based plastics, such as Human toxicity and Acidification, while for bio-based alternatives, Water use and Freshwater Ecotoxicity are more significant. However, the analysis highlighted that both types of materials present main impacts on Climate Change, Resource use fossils, Particulate matter, Resource use - minerals and metals, and Photochemical ozone formation, Acidification.

The analysis, with a cradle-to-grave scope, also includes the EoL stage. In general, this EoL process (waste treatment) has significant impact on the reference scenario but is less relevant for bio-based and biodegradable materials. This is because most of the bio-based solutions are also biodegradable and the impacts of industrial or home composting are limited. In parallel, the environmental hotspots



of the technological solutions for generating valuable coproducts like fertilisers, animal feed from BSF bioconversion, and biogas from anaerobic digestion have been evaluated. These technologies could also offer interesting EoL treatment opportunities for the biodegradable solutions.

For the EoL stage of the end of life of the products, a variable mix depending on material type is considered: open burning (10%), open dumping (80%) and landfill (10%) [13], but for the purposes of life cycle modelling, the open-dumped fraction has been treated as if it were open-burnt for the reference materials EoL. 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 underestimated as it does not consider plastic effects on biota [3]. This modelling assumption is grounded in two considerations: (i) open dumping and open burning frequently co-occur in the studied contexts, making this assumption contextually plausible, (ii) the EF3.1 method provides a more detailed and representative characterisation of the impacts of open burning, especially regarding air pollution and climate change indicators. However, it must be noted that the environmental impacts of open dumping concern long-term pollution, whereas open burning causes high emissions of air pollutants [3].

Bio-based materials solutions

Different bio-based materials were analysed as a result of the search for innovative solutions of Bio4HUMAN. Among these materials, the following were evaluated using LCA methodologies [3]: PLA, compostable pouch: cellophane, Polybutylene Adipate Terephthalate (PBAT), PLA and metallic cellulose, polyester from starch, Mycelium-based material and bio-based building insulation materials.

As result of this analysis, the conclusions regarding PLA are shown in the following Figure 1. This bio-based material is one of the most commonly used bioplastics worldwide and the base of multiple solutions of Bio4HUMAN project. PLA is based on the polymerisation of lactic acid, which is synthesised from glucose. In the study, different sources of PLA were considered: chemical and mechanical recycling, as well as virgin PLA derived from maize, sugarcane and biowaste. However, in the bio-based solutions analysed in Bio4HUMAN, PLA specifically refers to PLA synthesised from maize.

In the following figure, it is shown the example of the results of the hotspot analysis obtained for 1 kg of PLA bottles, to be used as oil and water container [3]. The production of PLA from maize cultivation has the highest environmental impacts, followed by blow moulding and extrusion of the material to shape the containers for oil or water. The main contributions of the PLA production from maize are on climate change, resource use fossils, water use, particulate matter and acidification. For extrusion and blow moulding the main impacts are on climate change and resource use fossils, due to the energy consumption of these processes. The EoL stage through industrial composting mainly affects climate change and freshwater ecotoxicity but represents less than 15% of total impacts. No nutrient credits are associated with PLA composting, as it lacks N, P, and K, although it improves soil structure.

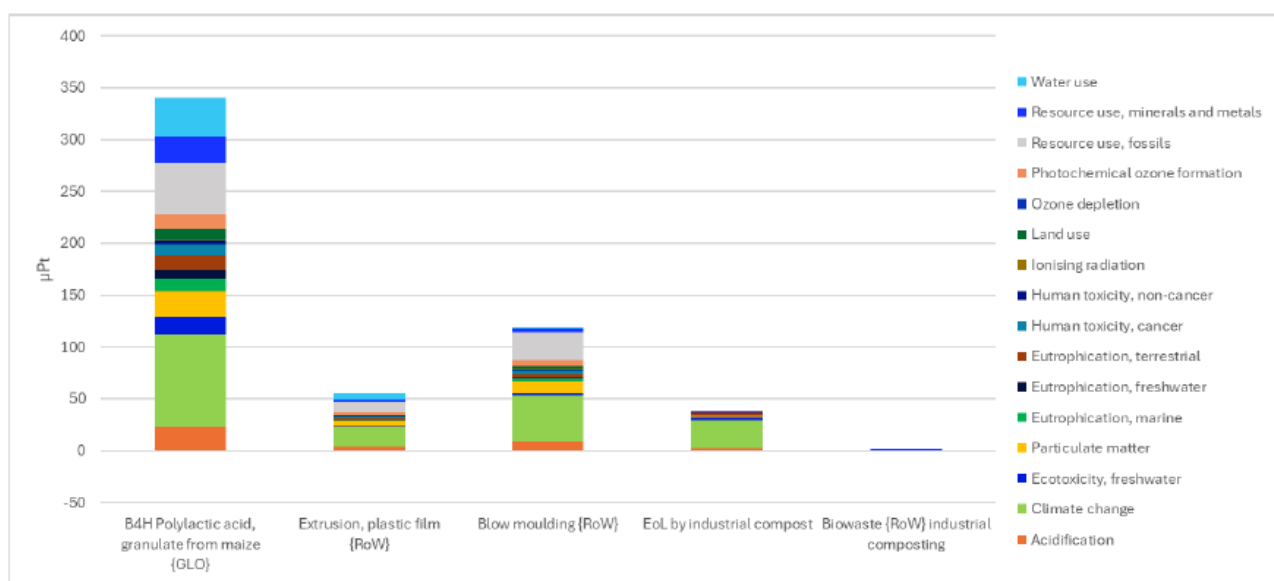


Figure 1. Results of the PLA example for oil and water container, single score results: 1 kg of PLA
Source: Deliverable 5.2. Hotspot analysis of the current and innovative solution, Bio4HUMAN [13]

Other indicators analysed in Bio4HUMAN that should be highlighted are the effects of plastics on biota (Impact World +), ecosystem quality (Impact World +) and biogenic carbon uptake (EN 15804+A2). This first indicator, plastic effects on biota, reflects intrinsic potential for toxicity on ecosystems when plastic leakage occurs. Microplastics are associated with open dumping and unsanitary landfills (i.e. current reference EoL scenario) of plastics. Also, PLA is not always biodegradable without industrial composting and can release microplastics if it leaks in nature; however, its effect on biota per kg (7.8 PDF·m²·yr) is significantly lower than HDPE (481.3 PDF·m²·yr) or LDPE (256.3 PD m² yr) due to its density and limited water impact. Proper handling is however still necessary to limit impacts of the solution materials on the ecosystems [6].

The ecosystem quality indicator, part of the Impact World+ v2.1 method, aggregates multiple environmental impacts—such as climate change, land use, water pollution, and plastic effects on biota—into a single measure of biodiversity damage. This indicator complements EF3.1 by adding an endpoint perspective and highlights how both fossil-based and bio-based materials affect ecosystem viability. The result per 1 kg PLA bottle for oil and water for this indicator is 5.35 PDF.m².year [3].

The carbon uptake represents the amount of biogenic CO₂ that is captured by a material, that can temporarily store CO₂ out of the atmosphere. The carbon uptake result per 1kg of solution material, PLA bottle for oil and water considering the emissions of the EoL, is 0.75 kg CO₂ eq. [3].



End of life: technological solutions

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. Five types of digesters are studied in Bio4HUMAN 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. In this technical communication a brief summary of the results for the AD is shown. To revise the results of the different end of life technological solutions, please refer to D5.2 [13].

The results presented in Figure 2, cover the micro-biogas digester for any sort of biowaste, working in mesophilic conditions. 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. Infrastructure is not included in the analysis, since the quantity of the different materials is lacking, and the impact of it is usually low, given the lifetime of the infrastructure. In this specific digester, electricity is the main contributor to the different environmental impact categories: Climate Change, Resource Use, fossils, Particulate matter and Acidification.

In addition, it is interesting to study the benefits of producing biogas and obtaining nutrient-rich digestate. These co-products avoid impacts associated with heat generation and fertilisers manufacturing. The impacts of credits are presented in the following figure. The results show that heat generation, as well as the fertilisers contained in the digestate, all present significant credits.

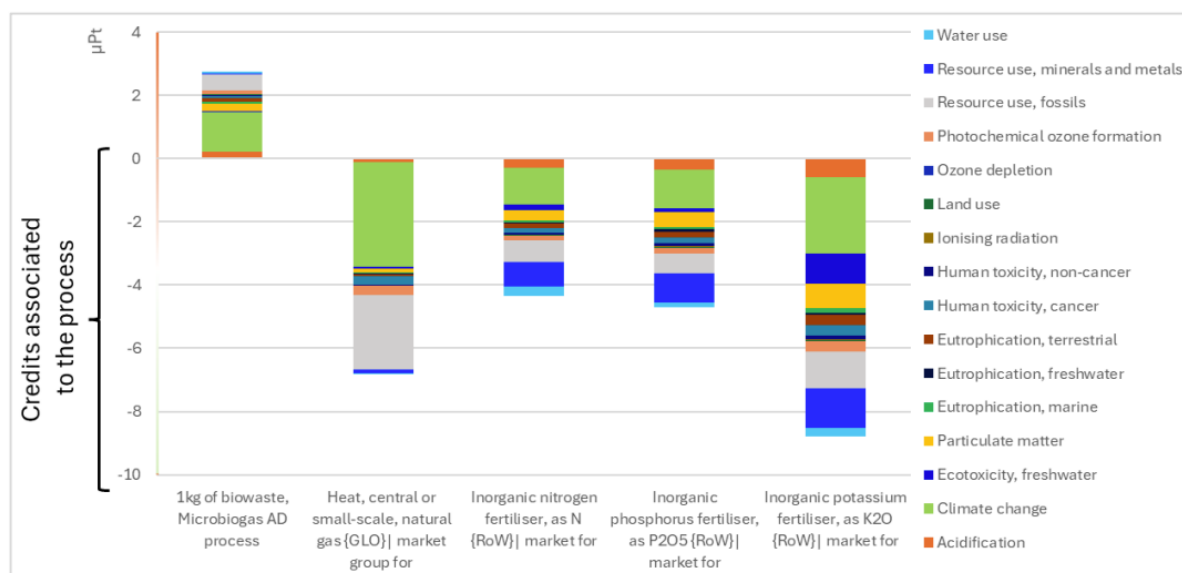


Figure 2. Results of the Biowaste treatment in Microbiogas AD, Single score results: 1kg of biowaste
Source: Deliverable 5.2. Hotspot analysis of the current and innovative solution, Bio4HUMAN [13]

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.

Reference scenarios

In the Bio4HUMAN project, different reference materials were assessed: HDPE and LDPE containers, multimaterial packaging film: Two PE layers metallised with Polyethylene Terephthalate (PET), Polypropylene (PP) bag, disposable PP pads, Polyester fibres from PET, LDPE film, Polyvinyl Chloride (PVC) tape. The results obtained per 1 kg of HDPE and LDPE containers are included as an example in Figure 3 and Figure 4 [3]. In this material, the hotspot analysis concluded that LDPE and HDPE production processes have the highest environmental impacts, followed by blow moulding to produce the containers. It can also be noted that EoL, by open burning, 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.

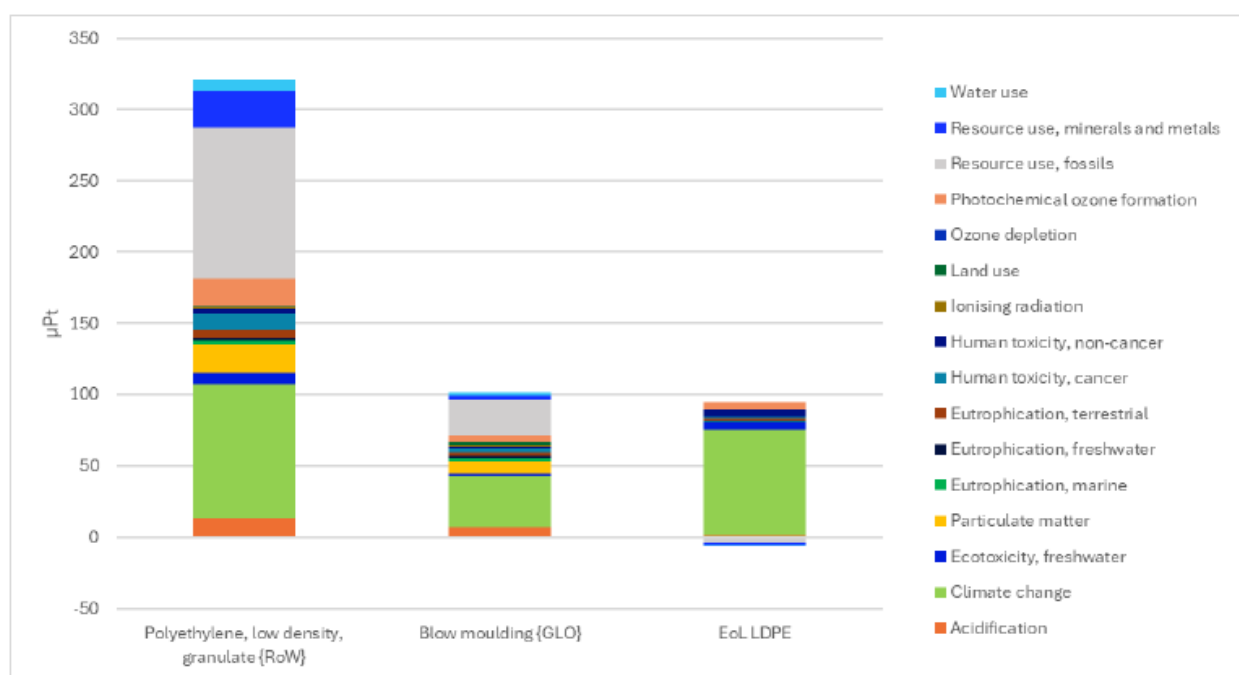


Figure 3. Results of the example of the water container, single score results: 1 kg of LDPE
Source: Deliverable 5.2. Hotspot analysis of the current and innovative solution, Bio4HUMAN [13]

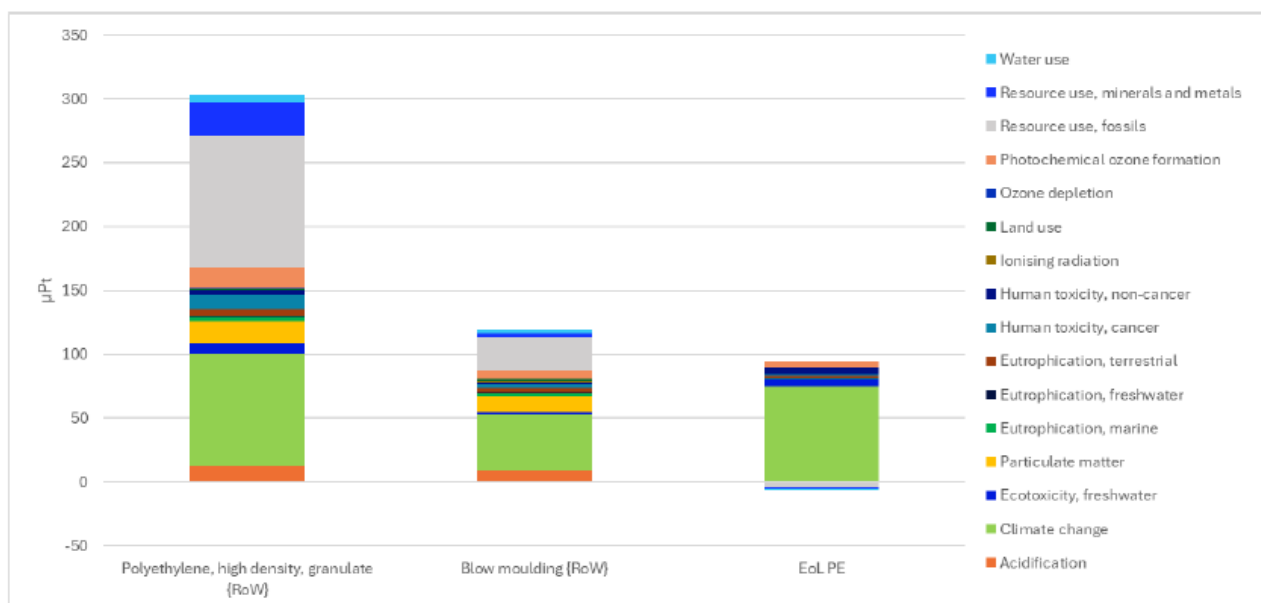


Figure 4. Results of the example of the oil container, single score results: 1 kg of HDPE
Source: Deliverable 5.2. Hotspot analysis of the current and innovative solution, Bio4HUMAN [13]

Regarding the physical effects on biota, 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 also tend to persist longer times on surfaces and smother them. As stated in the previous section, HDPE and LDPE have higher impacts on biota than PLA (if the materials biodegrade properly, they do not produce microplastics). In relation to the Ecosystem quality indicator, the results obtained for 1kg of HDPE oil container and LDPE water container are 6.52 PDF m² year and 6.44 PDF m² year [3].

The materials studied for the reference scenario are fossil-based. Therefore, no carbon content can be associated with biogenic carbon. The indicator does not provide added value in the reference scenario, but it helps to highlight the absence of biogenic carbon capture in fossil-based solutions, a feature that is addressed by the solutions analysed in the project [3].



4. Conclusion: Circular economic opportunities

Circularity, according to the Ellen MacArthur Foundation [20], is understood within the framework of the **circular economy**, which is an economic model designed to be **regenerative by principle** and seeks to break with the traditional linear pattern of “take, make, dispose.” The main principles of the circular economy, which are addressed in Bio4HUMAN are: 1) Eliminate waste and pollution; 2) Circulate products and materials (at their highest value); and 3) Regenerate nature.

The Bio4HUMAN project applies these three principles primarily through the sustainable management of solid waste generated during humanitarian operations. First, the project aims to contribute to the elimination of waste and pollution from the designed stage. For this reason, Bio4HUMAN promotes bio-based and biodegradable solutions that reduce solid waste generated in humanitarian kits and supplies (such as plastic). Consequently, practices like open dumping and open burning, which contaminate soil, water and air are avoided.

The second principle- circulating products and materials at their highest value- is implemented by encouraging the use of bio-based materials that have different end-of- life options, other than open dumping or burning. In this sense, these materials can be processed through composting systems, anaerobic digestion or Black Soldier Fly (BSF) treatment. Therefore, these bio-based materials are suitable to be treated in environments with limited infrastructure, avoiding accumulation of waste and mitigating health and environmental risks.

Finally, the selected end-of-life technologies and bio-based products contribute to returning nutrients to the soil through composting and reducing dependence on fossil-based materials, promoting regeneration of local ecosystems. These solutions can be treated locally, minimizing pollution and health hazards associated with fossil material disposal.

Additionally, the project conducts Life Cycle Sustainability Assessment (environmental, economic and social) to ensure that proposed solutions are sustainable and replicable in other humanitarian contexts. This comprehensive analysis that is carried out in Bio4HUMAN enables the development of tools for humanitarian actors, facilitating the implementation of circular solutions in future crisis.



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