LLIN LCA Analysis Report

I. Description

Long-Lasting Insecticidal Nets (LLINs) are critical commodities in global malaria prevention efforts, particularly in humanitarian and low-resource settings. However, their production, international transport, and end-of-life disposal generates environmental impacts. This study aims to evaluate the life-cycle environmental impacts of a standard LLIN and to explore alternative scenarios that may mitigate these impacts. Specifically, a cradle-to-grave analysis of a LLIN is conducted to better understand key drivers for climate change and human health impact, as well as to assess potential pathways to reduce these impacts. The baseline product consists of a polyester-based LLIN, manufactured in China, transported approximately 10,000 kilometres by sea to regional logistics hubs - such as those in East Africa - and distributed within a radius of 1,500 kilometres.

Supply information is as follows:

- Materials: Polyethylene, Alpha-Cypermethrin, Chlorfenapyr
- Weight: 530 grams.
- Packaging: packaging film and tape packing bale of 50 nets.
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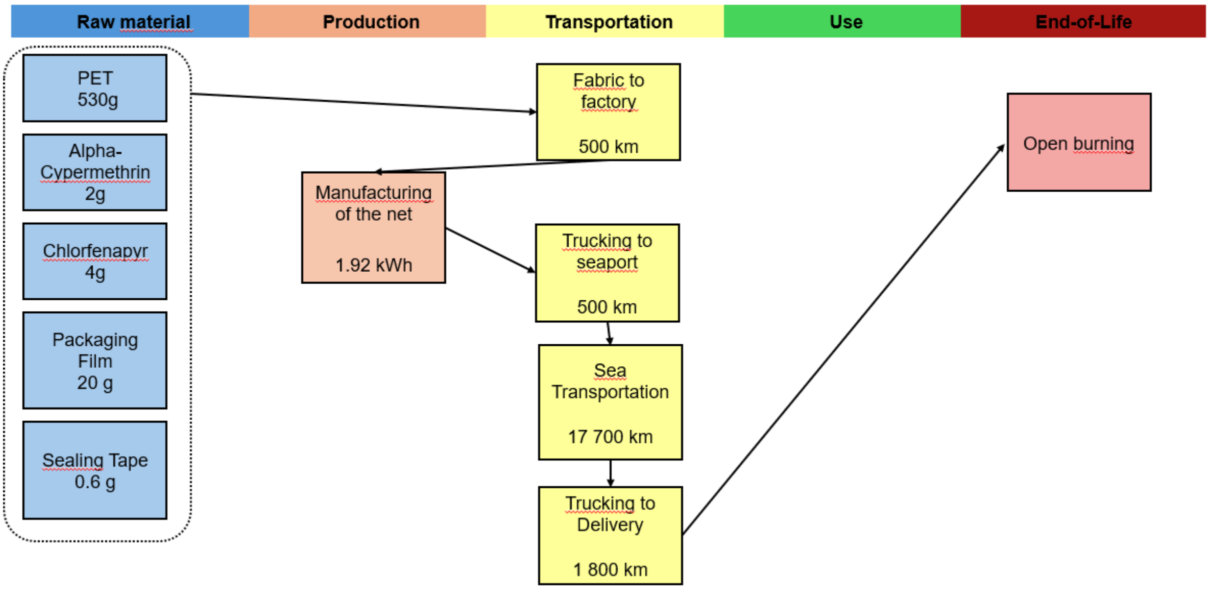
II. Methodology

Life Cycle Assessment is a standard methodology used to estimate the potential environmental impacts linked to the entire life cycle of a product or system (ISO 14040, 14044, 14067). The scope herein is a cradle-to-grave analysis, including raw material acquisition, production, transportation, use, and end-of-life (EoL) treatment. See Figure 2 below for the LCA of the baseline scenario, a LLIN net currently used by humanitarian organisations.



To perform these studies, data from from the Ecoinvent 3.11 cut-off system model is used, which allocates the entire impact of the material to its primary user without any 'rewards' for its potential for being recycled. EU Commission Environmental Footprint Method 3.1 and indicators were used to evaluate the scenarios using two categories. The human health indicator was aggregated to measure multiple impacts on human health as shown below. It was also normalized for one citizen so as to aggregate and represent as a single score for human health.

Both of the following indicators were weighted using the EF3.0 approach (10).

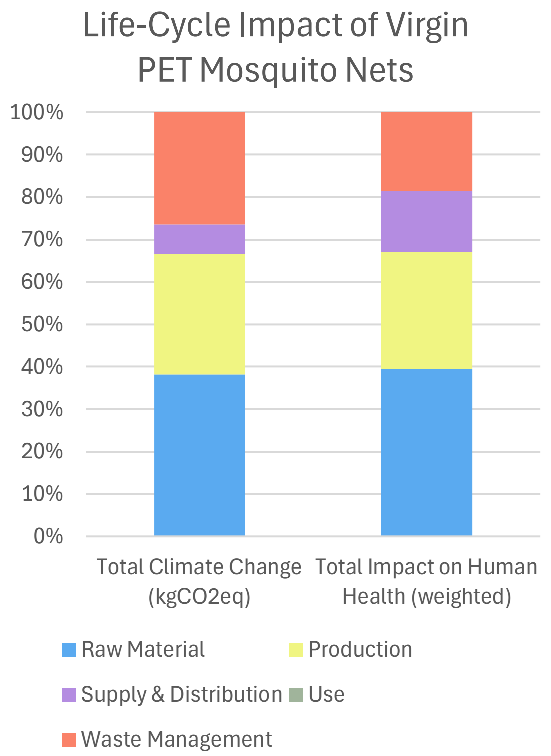
1. **Climate Change**: Global Warming Potential (GWP100 - limited to a 100-year timeframe)

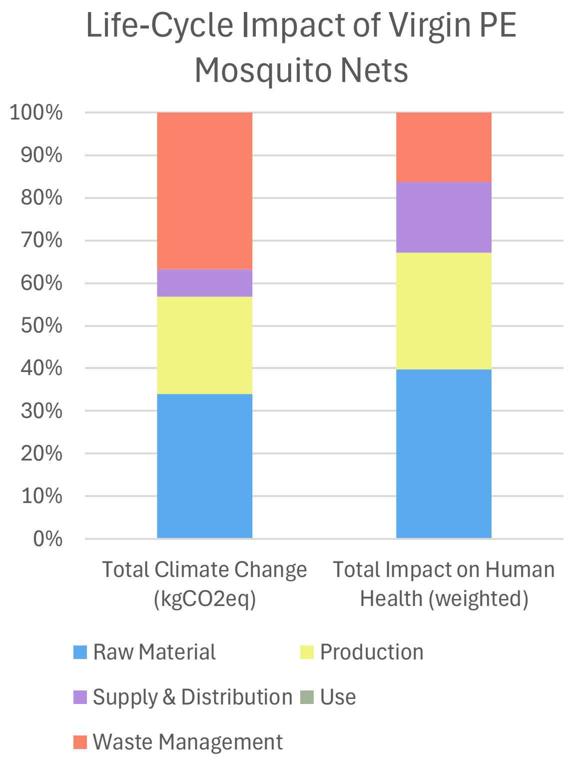
2. **Impact on Human Health**:

- Human Toxicity: Carcinogenic and Non-carcinogenic
- Ionising Radiation
- Particulate Matter Formation
- Photochemical Oxidant Formation

Assumptions

LIFE-CYCLE STAGE	PARAMETER	DESCRIPTION OF MODEL
GENERAL	Field Context	Assessing the impact of the two main type of Long-Lasting Insecticide Nets (LLIN) distributed by humanitarian organisations and prequalified by WHO.
Raw Material	Bill of Materials	Virgin PET (net weight 530g, 150 D) or Virgin PE (net weight 350g 100 D)
	Packaging	PE Film with packing tape
Production	Manufacturing Location	China
	Manufacturing Processes	Modelled as electricity consumption (literature)
Supply & Distribution	Transport Chain	Trucking 500 km to seaport Sea 10000 km (Mombasa) Trucking 300 km to warehouse Trucking 1500 km to distribution point
Use	Lifespan	Virgin PET: 2 years (holes begin to emerge in the PET fabric) Virgin PE: 3 years (standard life of insecticides in the net)
	Usage Processes	None
Waste Management	Product Disposal Method	Open burning
	Packaging Disposal Method	Open burning (no transport)





III. Scenario rationale

a. Raw material choice

The materials used in the production of LLINs are typically virgin polyethylene (PE) or polyester (PET). Baseline PET nets are heavier (150 denier – approximately 530 g), while PE nets use a lighter material (100 denier – approximately 350 g). In addition, the thicker fibers of PE nets help prevent hole formation and improve reparability, contributing to a longer lifespan—three years for PE nets compared to two years for PET nets.

In this study, the baseline scenario is defined as a LLIN made from virgin PET. This reference case is compared against alternative material options to assess the maximum potential for emissions reduction through material substitution. Specifically, three alternative scenarios are modelled: (1) switching from PET to virgin PE; (2) using 100% recycled PET; and (3) using 100% recycled PE. For both recycled material scenarios, two quality levels are considered - high-quality recycled plastic, sourced from controlled and industrial recycling streams, and lower-quality recycled plastic, which presents shorter durability and higher degradation over time.

Previous research has assessed various blends of virgin and recycled plastic, evaluating mechanical properties such as tensile strength, elastic modulus, elongation at break, and density. Optimal performance has typically been observed with blends around 30% recycled and 70% virgin plastic, while significant degradation – particularly in elongation at break – has been reported in blends exceeding 90% recycled content. In this study, however, a 100% recycled scenario is modelled to capture the upper limit of potential climate benefits, regardless of current technical limitations as they are not specific to the LLIN processes of production.

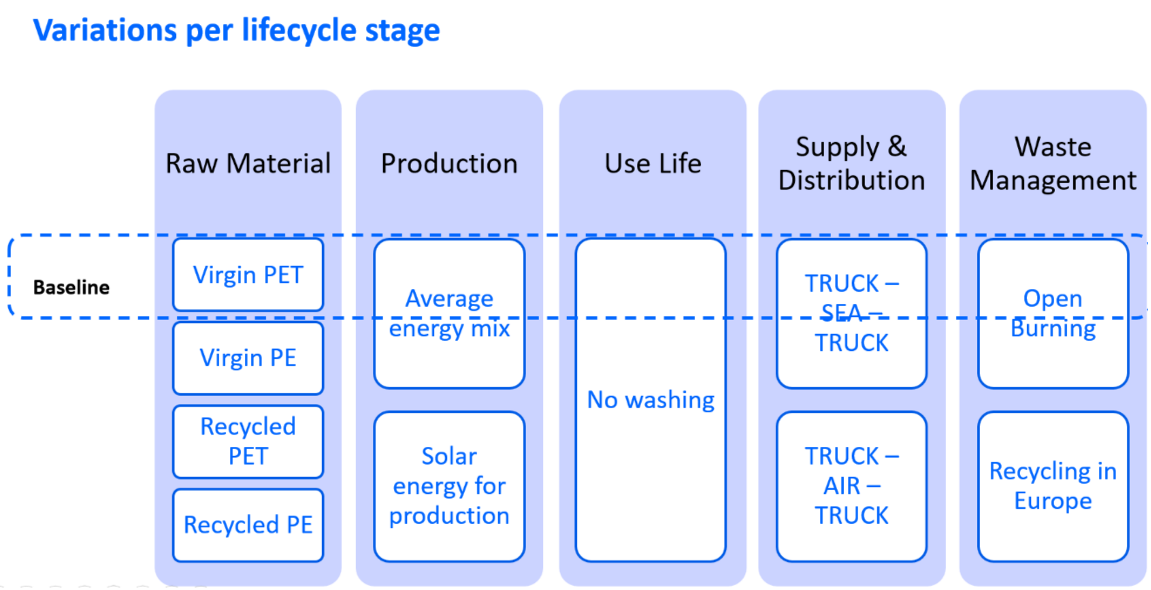
b. Energy in production

In this study the national electricity grid mix from China was used as the baseline. Grid emission factors refer to the greenhouse gas emissions per unit of electricity generated by the power grid in a specific region and timeframe. Emissions were compared with installing solar at the production site.

c. End-of-Life

While LLINs often have diverse end-of-life pathways – including informal reuse as clothes, household decorations, or other secondary purposes – most ultimately end up being incinerated or burnt in the open, due to the absence of structured waste management systems in many deployment contexts. Despite their temporary repurposing, the predominant fate of LLINs remains combustion, which contributes to environmental and human health impacts.

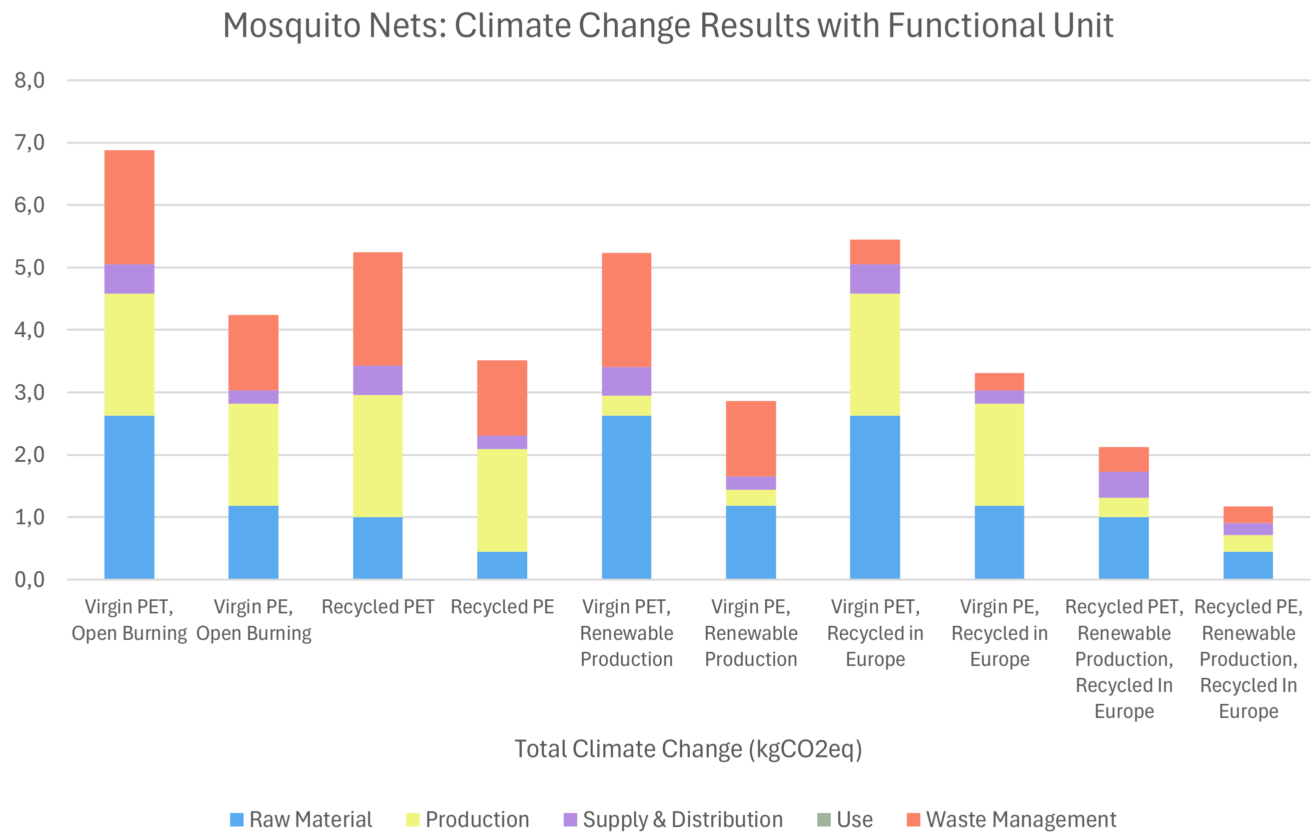
To estimate the potential environmental benefits from improving end-of-life management, this study models a scenario in which used LLINs are collected and returned to Europe for recycling – representing a theoretical best-case scenario. This assumes the existence of a reverse logistics chain capable of retrieving post-use nets from the field. Although such infrastructure is currently lacking or extremely limited in most settings where LLINs are distributed, this scenario allows us to quantify the maximum potential reduction in life-cycle impacts associated with end-of-life recycling, rather than disposal through uncontrolled burning.

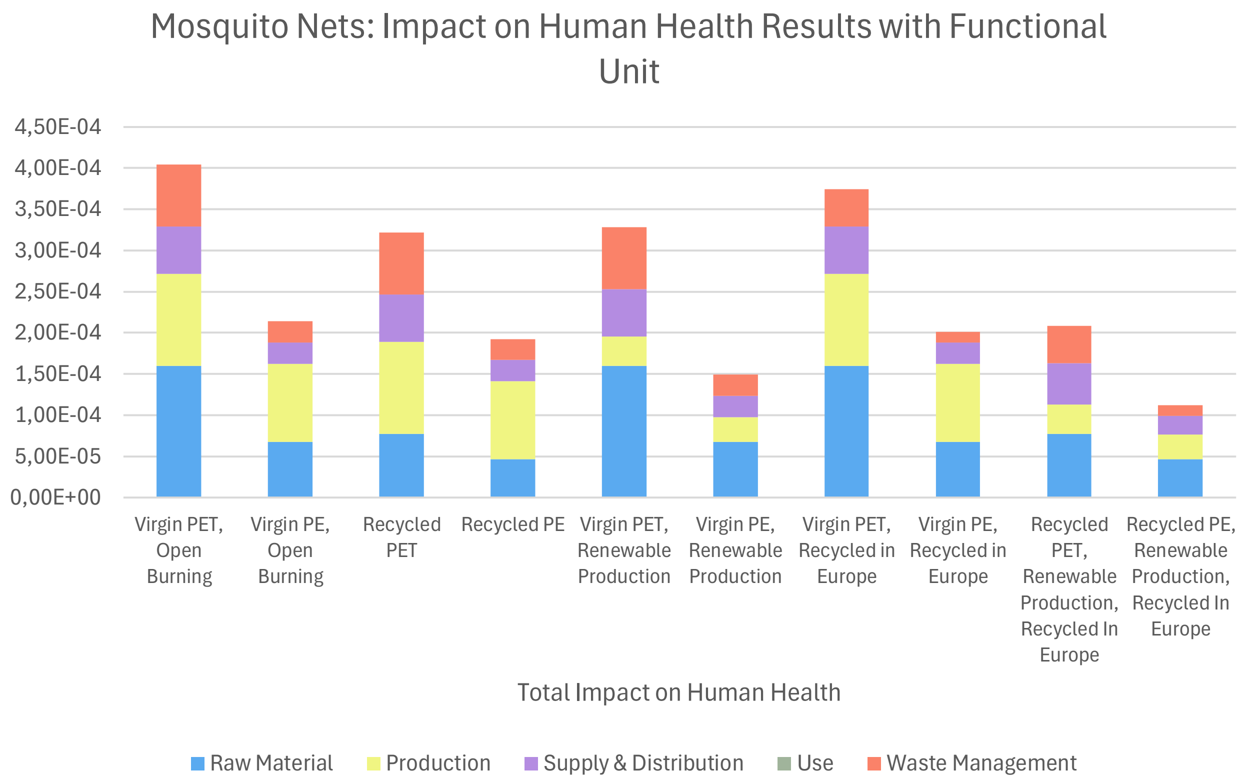


IV. Results and Discussion

First, thanks to a lighter material and a longer lifespan (3 years instead of 2), the use of PE nets instead of PET nets are theoretically 38% better regarding climate change (CC) and 47% better regarding human health impact (HH). Moreover, regarding the baseline products, here are the results of the different scenarios.

	Material		**Production**		**End-of-Life**		**Total**	
	PET	**PE**	**PET**	**PE**	**PET**	**PE**	**PET**	**PE**
Raw material choice	-62% CC -52% HH	-62% CC -31% HH	0%	0%	0%	0%	-24% CC -20% HH	-17% CC -10% HH
Energy in production	0%	0%	-84% CC -68% HH	-84% CC -68% HH	0%	0%	-24% CC -19% HH	-33% CC -30% HH
End-of-life treatment	0%	0%	0%	0%	-78% CC -41% HH	-77% CC -49% HH	-21% CC -8% HH	-22% CC -6% HH
Combination of 3	-62% CC -52% HH	-62% CC -31% HH	-84% CC -68% HH	-84% CC -68% HH	-78% CC -41% HH	-77% CC -49% HH	-69% CC -49% HH	-72% CC -48% HH





The table below shows the gains when applying individual actions, as well as combinations of actions which can achieve significant reduction potential.

Reduction Potential	Single Actions	Combined Actions
>75%		Use Recycled PE net produced with renewable energy and manage waste
30-75%		Use Recycled PET net produced with renewable energy and manage waste
30-75%		Use Recycled PE net or Virgin PE net but produced with renewable energy instead of PET net
15-30%	Use PET net instead of PE net	
15-30%	Switching from fossil fuel-based electricity mix to solar (country grid dependant)	

15-30%	Replacing virgin PET with good quality recycled PET when importing recycled pellets from EU	
15-30%	Avoid open burning of nets at the end-of-life	

Results by Category:

a. Switching Material

Switching from polyester (PET) to polyethylene (PE) in LLIN production offers substantial environmental benefits. The change reduces climate change impacts by 38% and human health impacts by 15%. These reductions are primarily due to the lower density of PE, which makes it lighter and less resource-intensive to produce and transport. In addition, PE has demonstrated a longer lifespan under field conditions compared to PET, further amplifying its environmental advantage by extending the product's functional use phase.

b. Recycled Material

Using recycled materials can lead to significant reductions in both greenhouse gas emissions and human health impacts. In the case of PET, substituting virgin with 100% recycled PET yields a 48% reduction in carbon emissions and a 26% reduction in human health-related impacts. These benefits arise mainly from avoiding the energy-intensive production of virgin plastic and the associated upstream impacts. While logistical and quality control challenges remain for implementing large-scale recycling in LLIN supply chains, the environmental potential of recycled PET is considerable.

c. Energy

Replacing electricity from the fossil-fuel-dominated national grid with solar photovoltaic (PV) energy at production sites can lead to substantial environmental gains. For LLINs made from PET, switching to solar electricity reduces production-phase emissions by 24% and human health impacts by 19%. This is particularly relevant in countries like China, where the electricity grid is heavily reliant on coal. Even when accounting for the full life cycle of solar energy - including the manufacture, transport, and end-of-life treatment of solar panels - solar PV remains cleaner, contributing to an overall 18% reduction in GHG emissions and 13% in human health burdens across the product life cycle.

d. Waste Management

While LLINs are often repurposed informally - as wedding dresses, decorations, or household items - the majority eventually end up being openly burned due to the lack of formal waste infrastructure in distribution areas. This practice poses major risks to human health and contributes to climate change. In an optimistic scenario where end-of-life LLINs are collected, transported back to Europe, and properly recycled, climate change impacts could be reduced by up to 20%, and human health impacts by as much as 23%. These reductions highlight the importance of developing structured waste collection and reverse logistics systems, even in resource-constrained settings, to unlock the potential benefits of recycling and proper disposal.

V. Discussion and Conclusions (Cara will reduce redundancies)

As illustrated in the spider plots, the interventions that yield the greatest reductions in both climate change and human health impacts are consistent across categories - primarily material choice and end-of-life treatment. Switching from polyester (PET) to polyethylene (PE) shows substantial improvements, owing to PE's lighter weight and longer field-tested durability. Likewise, substituting virgin PET with high-quality recycled PET results in significant reductions in environmental burden - up to 48% in GHG emissions and 26% in human health impacts.

End-of-life management also plays a crucial role. Transitioning from open burning or uncontrolled incineration to structured sanitary landfilling or, in an ideal scenario, full recycling, leads to meaningful impact reductions. In the most optimistic case, where LLINs are collected and recycled in Europe, end-of-life interventions can reduce climate impacts by up to 20% and human health impacts by 23%. While open dumping may offer lower immediate emissions than burning, it introduces serious risks of long-term toxicity to soil and water.

Replacing fossil-fuel-heavy electricity grids with solar energy at the production stage further amplifies gains. For PET LLINs, solar-powered production reduces emissions by 24% and human health impacts by 19%, with overall life cycle improvements even when including the production and disposal of PV systems.

Conclusion

This study demonstrates that substantial reductions in greenhouse gas emissions and human health impacts can be achieved across the life cycle of LLINs by acting on material choice, energy sources, and waste management practices.

For LLINs made of PET, progressive decarbonation strategies yield the following results:

- Using 100% recycled PET instead of virgin PET reduces impacts by 🔻 48% (climate change) and 🔻 26% (human health).
- Switching from a fossil-fuel-based electricity mix to solar energy reduces impacts by an additional 🔻 24% (climate change) and 🔻 19% (human health).

- Improving end-of-life management - from open burning to controlled recycling or sanitary landfilling - adds further reductions of up to 🔻 20% (climate change) and 🔻 23% (human health).

When combining all three levers - recycled material, solar energy, and improved waste treatment - the overall reduction reaches:

- 🔻 69% in climate change impacts
- 🔻 48% in human health impacts

Alternatively, switching from PET to PE provides inherent material-related benefits due to PE's lighter weight and better durability in field conditions:

- 🔻 38% in climate change impacts
- 🔻 15% in human health impacts

When this PE-based system is optimized with recycled PE, solar-powered production, and improved end-of-life treatment, maximum reductions reach:

- 🔻 82% in climate change impacts
- 🔻 51% in human health impacts

These results underscore the importance of integrated life-cycle strategies. While material substitution alone can yield immediate gains, combining it with decarbonized energy and responsible waste management unlocks the full mitigation potential of LLIN supply chains.

References

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