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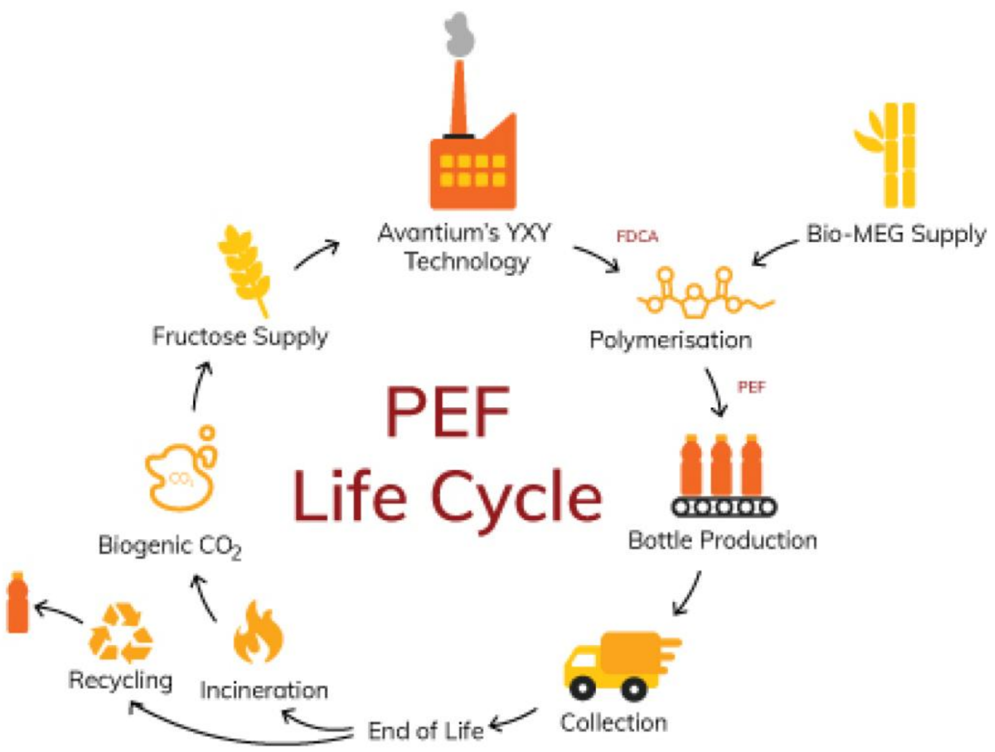
releaf® (PEF): Rethinking Plastics for a Low-Carbon and Circular Future

An accessible overview of the updated Life Cycle Assessment (2026) of PEF, branded as releaf®



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Executive summary

The updated Life Cycle Assessment (LCA) of releaf®, Avantium's plant-based polymer PEF (polyethylene furanoate), shows that greenhouse gas emissions can be reduced by up to 88% in beverage bottle applications compared to conventional PET (polyethylene terephthalate) under representative European conditions.

These results are based on a functional unit of a 500 mL beverage bottle delivering equivalent performance. The strongest reductions are achieved in monolayer PEF bottles, where the material's superior properties enable both lower material use and a fundamentally different carbon balance.

This assessment, conducted through a collaboration between Avantium, Tereos and nova Institut and supported by the European Commission's PEFerence project, provides one of the most comprehensive and industrially grounded evaluations of PEF to date. It confirms that a meaningful reduction in the environmental footprint of plastics can be achieved while maintaining performance and compatibility with existing recycling systems.

At a time when the plastics industry faces increasing pressure to reduce its dependence on fossil feedstocks, releaf® demonstrates how renewable carbon, high material performance and circularity can be combined in a practical and scalable solution.

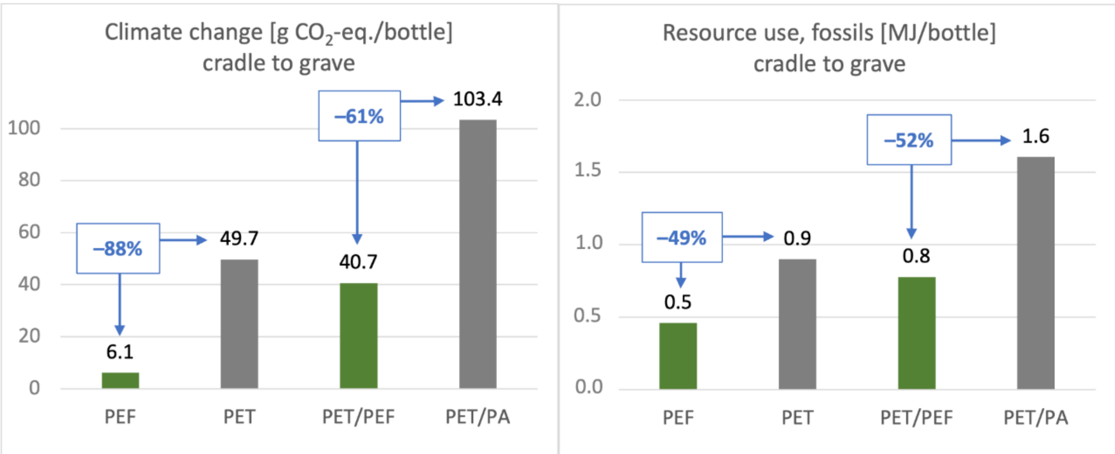

Figure 1. Climate change (CC) & fossil resource use (RF) contributors of PEF & PET-based monolayer & multilayer bottles, cradle to grave.

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1. A step change in carbon impact: up to 88% reduction

The updated Life Cycle Assessment (LCA) of releaf®, Avantium's plant-based polymer PEF (polyethylene furanoate), shows a clear and significant outcome. At resin level, emissions can be reduced by up to 71%[1] when compared to PET (polyethylene terephthalate). At application level, this translates into reductions of up to 88% in 500 mL beverage bottle applications.

The highest reductions, in this study, are achieved in monolayer releaf® bottles, where improved barrier properties and mechanical strength allow for lower material use while maintaining performance.

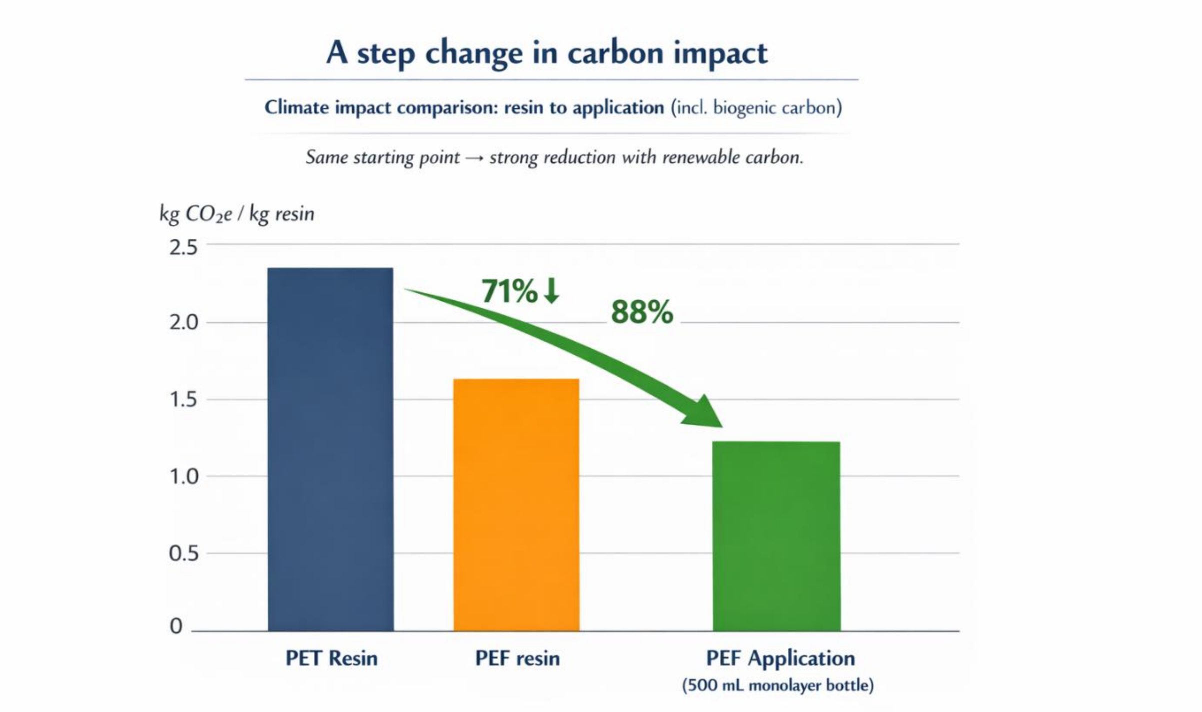

Figure 2. Climate impact comparison PET and PEF. Results are based on cradle-to-grave Life Cycle Assessment for a 500 mL beverage bottle delivering equivalent performance. Monolayer PEF bottles show the highest reduction, while multilayer PEF/PET solutions also outperform conventional PET/PA systems in both emissions and fossil resource use.

These results are based on a comprehensive study conducted through a joint collaboration between Avantium, Tereos and nova Institut, combining industrial expertise in technology, feedstock supply and sustainability analysis. The work has been supported by the European Commission through the PEFerence project. PEFerence has received funding from the Bio-based Industries Joint Undertaking under the European Union's Horizon 2020 research and innovation program (grant agreement no. 744409). The JU received support

[1] This includes biogenic carbon uptake

from the European Union's Horizon 2020 research and innovation program and Bio-based Industries Consortium.

The findings are published in a peer-reviewed scientific article titled *"Life Cycle Assessment of an Emerging, Innovative Biopolymer: Poly(ethylene furanoate)"*, representing one of the most comprehensive assessments of PEF at industrial scale to date.

Together, this combination of industrial data, independent expertise and public-private collaboration provides a robust foundation for understanding the environmental performance of releaf®.

2. Why plastics matter, and why they must change

Plastics play a critical role in modern society. They enable safe and efficient packaging, extend the shelf life of food and beverages, and reduce emissions associated with transport due to their low weight. In many applications, plastics help reduce overall environmental impact, for example by preventing food waste, which typically has a far larger carbon footprint than the packaging itself.

They also offer a unique combination of durability, flexibility and cost efficiency that is difficult to replicate with alternative materials at scale. Particularly in food and beverage packaging, there are currently few viable substitutes that deliver the same level of performance and safety.

At the same time, the current plastics system is largely dependent on fossil resources which are extracted, converted into materials, and ultimately released into the atmosphere. This dependence is increasingly under pressure from climate targets, regulatory developments and changing expectations from customers and investors.

"The challenge is not to eliminate plastics, but to transform how they are produced."

Recycling plays an essential role, but it cannot fully address the issue on its own. Material losses and growing demand mean that new material will continue to be needed. As a result, a more fundamental shift is required: moving from fossil carbon to renewable carbon.

3. A system under pressure: dependence on fossil feedstocks

Today's plastics system is largely based on fossil resources. This dependence is increasingly under pressure. Climate targets, regulatory developments, and expectations from customers, investors and society are accelerating the need for change. At the same time, global demand for plastics continues to grow, particularly in packaging applications.

Even with higher recycling rates, fossil-based plastics continue to introduce new carbon into the atmosphere. This creates a structural tension between the benefits plastics provide and the emissions they generate.

Addressing this challenge requires more than incremental improvements. It requires a shift to materials that deliver the same performance, but with a fundamentally different carbon balance.

4. A different carbon system

The key difference between conventional plastics and releaf® lies in the carbon cycle they operate in. Fossil-based plastics rely on carbon that has been stored underground for millions of years. When used, this carbon is released into the atmosphere, contributing to rising CO_2 concentrations. In contrast, releaf® uses renewable carbon derived from plants. During growth, plants absorb CO_2 from the atmosphere, which is then incorporated into the material. At the end of life, this carbon is released again, but it remains within the natural, short-term carbon cycle.

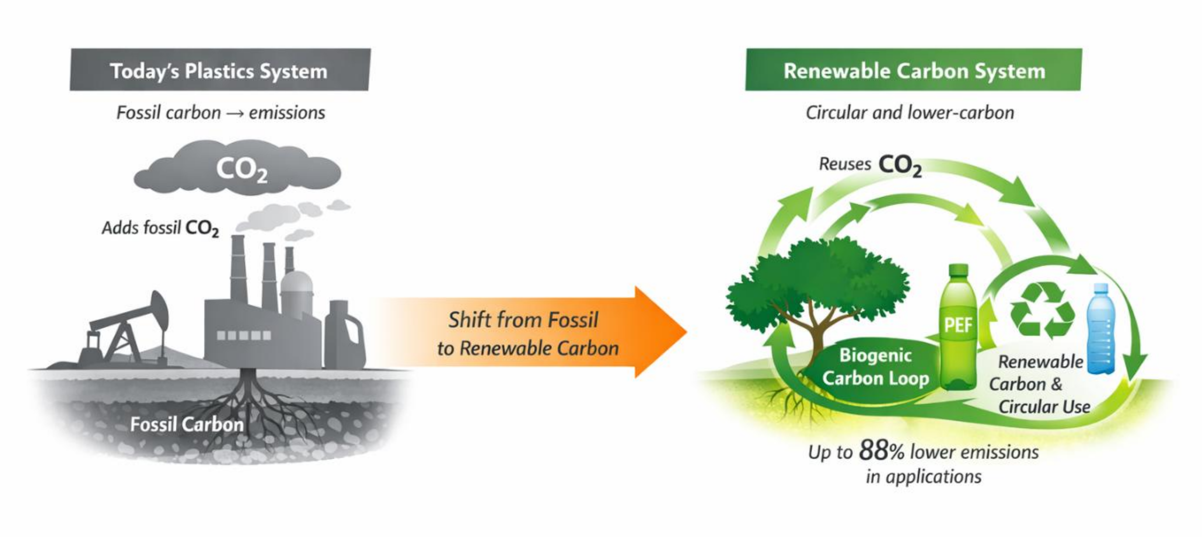

Figure 3. The carbon loop

This shift - from a linear fossil carbon system to a renewable, atmospheric carbon cycle - is central to the significant emission reductions observed in the LCA.

5. Introducing releaf®: performance, circularity and renewable carbon combined

Releaf® is Avantium's plant-based polymer, chemically known as PEF (polyethylene furanoate), designed for applications such as beverage bottles, packaging and fibres.

Its relevance lies not only in its renewable origin, but also in its performance. releaf® offers superior barrier properties and higher mechanical strength compared to PET, allowing it to protect products more effectively while using less material.

The improved properties of releaf® are particularly relevant in bottle applications. In monolayer designs, they enable a reduction in material use of around 20% compared to PET, while maintaining required performance.

PEF offers clear advantages in multilayer packaging applications. It can replace conventional barrier materials such as polyamides (PA), which are widely used in PET bottles but are not fully compatible with current recycling systems. In cases where a single layer of PET does not provide sufficient shelf life, PEF can be used as an effective barrier layer within multilayer PET bottles. Thanks to its excellent barrier performance and strong material similarity to PET, PEF is compatible with standard PET recycling processes and does not negatively affect the properties of recycled PET. As a result, PEF-based multilayer structures enable both lower emissions and improved recyclability compared to traditional PET/PA solutions, while supporting bottle-to-bottle recycling.

This combination of renewable carbon, improved performance and application compatibility makes releaf® a strong candidate for addressing the sustainability challenge in plastics.

6. Circular by design

A sustainable material must not only reduce emissions but also fit within a circular system. Releaf® is designed to be compatible with existing PET recycling infrastructure, enabling integration into established collection and recycling systems. Under current European conditions, where PET bottle recycling rates are around 72%, releaf® already shows a clear environmental advantage.

"Renewable carbon and recycling are not alternatives – they reinforce each other."

The assessment also shows that recycling and renewable carbon should not be seen as alternatives. Recycling reduces the need for virgin material, while renewable carbon reduces the impact of that material. Together, they reinforce each other and enable deeper reductions in environmental impact.

7. How the impact is assessed

The environmental performance of releaf® has been assessed using Life Cycle Assessment, a methodology that evaluates impact across the full life cycle of a product. This includes all stages, from biomass production and processing, through polymer manufacturing and application, to end-of-life treatment such as recycling and energy recovery.

To ensure fair and meaningful comparisons, a functional approach is used. Products are compared based on delivering the same performance. In packaging, this means that the improved properties of releaf®, such as better barrier performance and mechanical properties, are translated into realistic outcomes, rather than assuming identical product designs. For releaf®, this translates into reduced material use while extending the shelf life of the packaged product. For packaging applications, results are based on a functional unit of a 500 mL beverage bottle, designed to deliver the required packaging performance in terms of strength and product shelf life. This functional approach ensures that comparisons between PEF and PET systems reflect realistic product designs rather than assuming identical material use.

Property	Monolayer PEF Bottles	Monolayer PET Bottle	Multilayer PEF/PET Bottle	Multilayer PET/PA Bottle
Weight [g]	16–19	20–24	19.7	19.7
CO_2 shelf life [weeks]	>20	12	>12	>12
Storage & Transport	Good	Good	Good	Good
Recyclability	Full	Full	Full	Limited
Shape freedom	High	High	High	Mid
Bio-based content [%]	100	0	10	0

Table 1. PEF vs. PET solutions (500 mL) for carbonated soft drink containers

The updated LCA is based on industrially validated data and reflects conditions representative of future commercial production. It models the full value chain, including plant-based feedstocks, conversion into intermediates, polymer production via Avantium's YXY® Technology, and packaging manufacturing.

End-of-life is modelled based on current European conditions, including high recycling rates complemented by energy recovery for non-recycled fractions. In line with today's market reality, recycling rates of around 72% for beverage bottles are used as a representative baseline. Certain elements are excluded where their contribution is negligible or identical for both materials, such as caps, labels and emissions during the use phase.

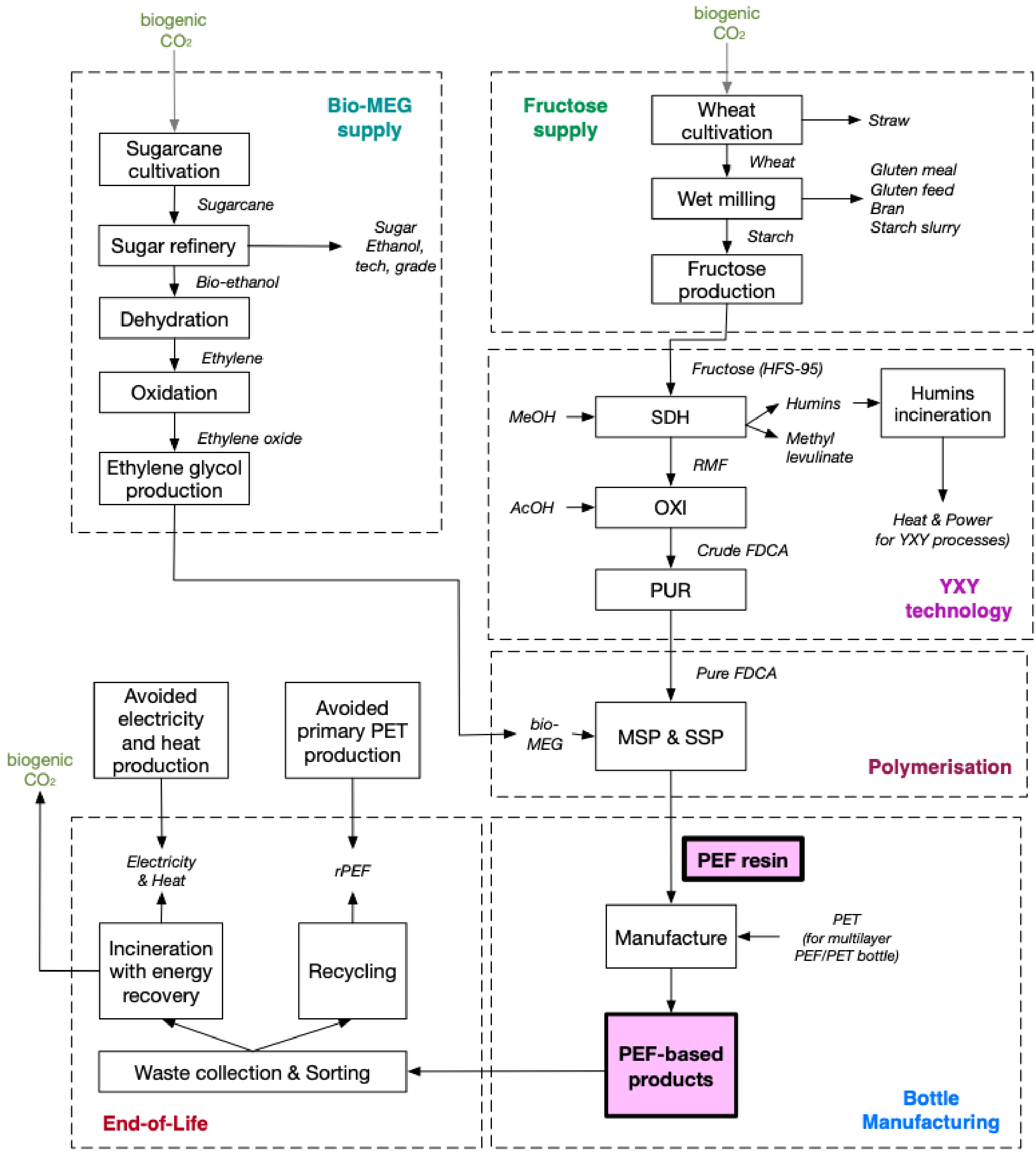

Figure 4. System boundaries for PEF systems

To provide a forward-looking perspective, the study includes sensitivity analyses covering different feedstocks, regional supply chains, recycling rates and levels of recycled content. This ensures that the results are robust across a range of realistic scenarios and future developments.

The reliability of the assessment is further supported by adherence to internationally recognized standards, including ISO 14040 and ISO 14044 for life cycle assessment and ISO 14067 for carbon footprinting. In addition, the study applies the European Environmental Footprint (EF 3.1) methodology, which evaluates multiple environmental categories and is widely used in policy and corporate sustainability frameworks.

A distinguishing element of the assessment is the explicit treatment of biogenic carbon. As releaf® is derived from plant-based feedstocks, CO_2 is absorbed during plant growth and incorporated into the material. This renewable carbon is released again at the end of life but remains part of a short-term natural carbon cycle, rather than introducing additional fossil carbon into the atmosphere.

Where processes generate multiple outputs, environmental impacts are allocated based on physical relationships, using mass-based allocation. Recycling is assessed using established modelling approaches that capture both the benefits of recycled content and the effects of material recovery at end of life.

A key strength of this assessment is the use of primary industrial data, supported by validated process models. Uncertainty has been explicitly assessed using statistical methods, including Monte Carlo analysis, confirming the robustness of the results. Conservative assumptions have been applied where necessary to ensure that the reported benefits are realistic and not overstated.

8. Where impacts remain, and how they can improve

As with all bio-based materials, the main environmental impacts arise from feedstock production and conversion processes. These include agricultural inputs such as land use, fertilizers and water. While this leads to higher impacts in certain categories, these represent a relatively small portion of the overall environmental profile.

Table 2. Cradle-to-gate impact assessment of PEF and PET resins according to EF 3.1

Impact	Abbreviation	Relevance [&]	PEF	PET	Unit
Acidification	AC	5.1%	1.84×10^{-2}	1.01×10^{-2}	mol H^+ eq.
Climate change (exc. BCU [#])	CC exc. BCU	19.2%	2.78×10^{0}	2.88×10^{0} [$]	kg CO_2-eq.
Climate change (inc. BCU [#,*])	CC inc. BCU	19.2%	8.43×10^{-1}	2.88×10^{0} [$]	kg CO_2-eq.
Particulate matter	PM	6.6%	1.78×10^{-7}	9.14×10^{-8}	disease incidence
Eutrophication, marine	EM	5.4%	1.44×10^{-2}	1.95×10^{-3}	kg N eq.
Eutrophication, freshwater	EF	3.5%	7.98×10^{-4}	5.06×10^{-4}	kg P eq.
Eutrophication, terrestrial	ET	5.1%	8.59×10^{-2}	1.94×10^{-2}	mol N eq.
Ionizing radiation	IR	2.2%	7.57×10^{-1}	2.27×10^{-1}	kBq U-235 eq.
Land use	LU	4.9%	2.03×10^{2}	1.50×10^{0}	Pt
Ozone depletion	OD	0.1%	2.11×10^{-7}	1.49×10^{-5}	kg CFC11 eq.
Photochemical ozone formation	OF	3.7%	1.29×10^{-2}	1.22×10^{-2}	kg NMVOC eq.
Resource use, fossils	RF	16.5%	5.20×10^{1}	7.00×10^{1}	MJ
Resource use, minerals and metals	RM	0.6%	2.06×10^{-6}	3.43×10^{-4}	kg Sb eq.
Water use	WU	2.1%	1.17×10^{0}	4.97×10^{-1}	m^3 deprivation

[&] For PEF results. After normalization and weighing using factors from EF3.1 impact assessment method [69]. [#] BCU = biogenic carbon uptake. * Extension to the climate change impact category using −1/+1 characterization factor for biogenic C-associated CO_2 uptake according to the stoichiometry. [$] Data for Europe (ecoinvent RER dataset). Global PET production lies at 3.20×10^{0} kg CO_2-eq.·kg^{-1}

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"The assessment therefore not only confirms the benefits of releaf®, but also highlights clear pathways for further improvement."

Importantly, the LCA highlights clear and actionable pathways for further improvement:

- **More sustainable feedstock sourcing**

  A significant share of environmental impact originates from agricultural production. Improvements can be achieved through responsible sourcing, certified supply chains and optimized agricultural practices that reduce fertiliser use, emissions and water consumption.

- **Switch to alternative feedstocks with lower impact**

  The analysis shows that feedstock choice has a strong influence on overall performance. In particular, sucrose-based feedstocks such as sugar beet and sugarcane can further reduce greenhouse gas emissions due to more efficient conversion processes.

- **Electrification of production processes**

  Replacing fossil-based energy with renewable electricity in key process steps, such as evaporation and heating, can significantly reduce emissions. For example, electrified process configurations show meaningful reductions in climate impact compared to conventional setups.

- **Further optimization of recycling systems**

  Higher recycling rates and increased recycled content further improve environmental performance. As recycling systems evolve, both bio-based carbon and material circularity can work together to reduce impacts even further.

- **Technology improvement**

  The technology is still at an early stage and is being compared with a highly optimized commodity. Improvements in performance, such as yield, are expected over time.

Together, these levers show that the environmental profile of releaf® is not only favourable today, but will continue to improve as technologies mature, supply chains develop and renewable energy becomes more widely available.

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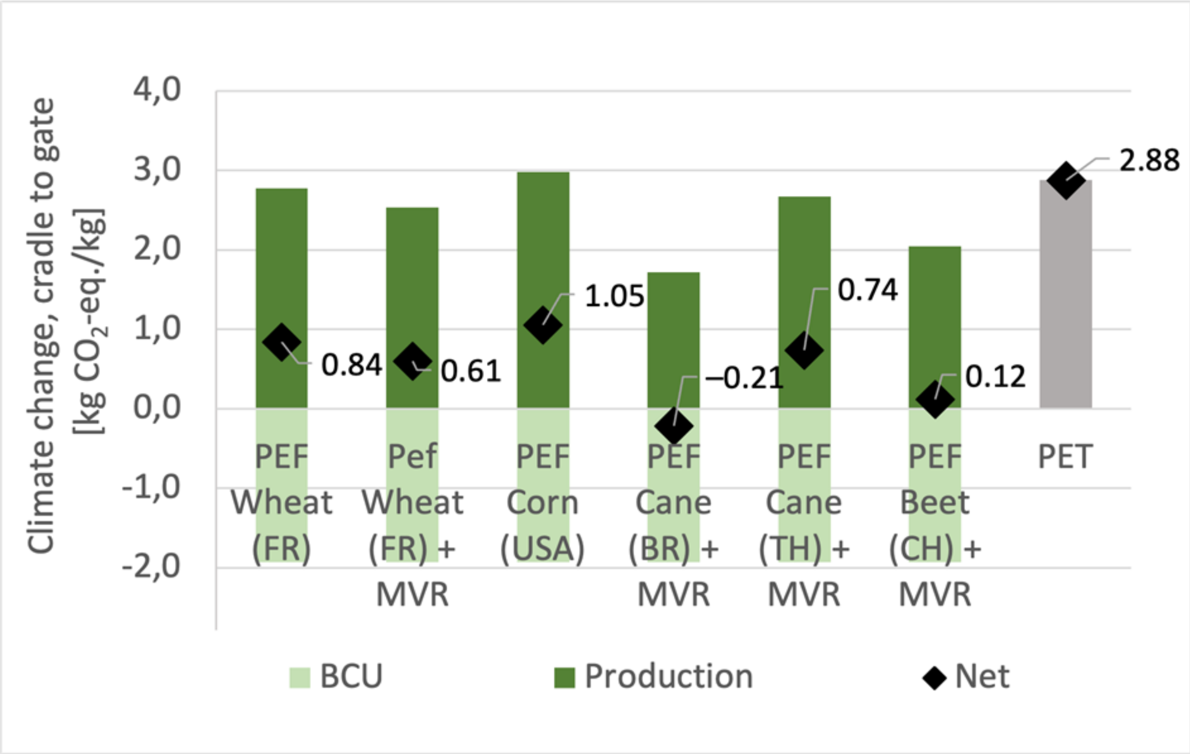

Figure 5. The effect of feedstock diversification (including electrical mechanical vapor recompression (eMVR) on fossil use

9. Conclusion: from fossil dependence to transition

The updated Life Cycle Assessment demonstrates that releaf® offers a credible and scalable pathway to reducing the environmental footprint of plastics, with emission reductions of up to 88% in key applications.

At the same time, it responds to a broader shift in the industry, where dependence on fossil feedstocks is increasingly under pressure. By combining renewable carbon, strong material performance and compatibility with existing recycling systems, releaf® enables a transition toward a plastics system that retains its essential benefits while significantly reducing its environmental impact.

The highest reductions are achieved in monolayer PEF bottles, where improved material properties enable lower material use and a fundamentally different carbon balance. At the same time, PEF also delivers clear benefits in multilayer applications by replacing conventional barrier materials and improving recyclability compared to existing PET/PA solutions.

The higher reduction of up to 88% compared to the Life Cycle Assessment conducted in 2024 reflects an improvement of the technology.. It combines improved material performance, full life cycle modelling including recycling, and a more complete and transparent treatment of renewable carbon.

Together, these findings show that transitioning to renewable carbon materials can deliver substantial climate benefits today, while also providing a robust foundation for further improvements as technologies, feedstocks and recycling systems continue to evolve.

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