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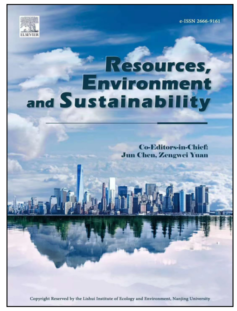

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Environmental Consequences of Replacing Polyethylene Packaging in the United States and Europe

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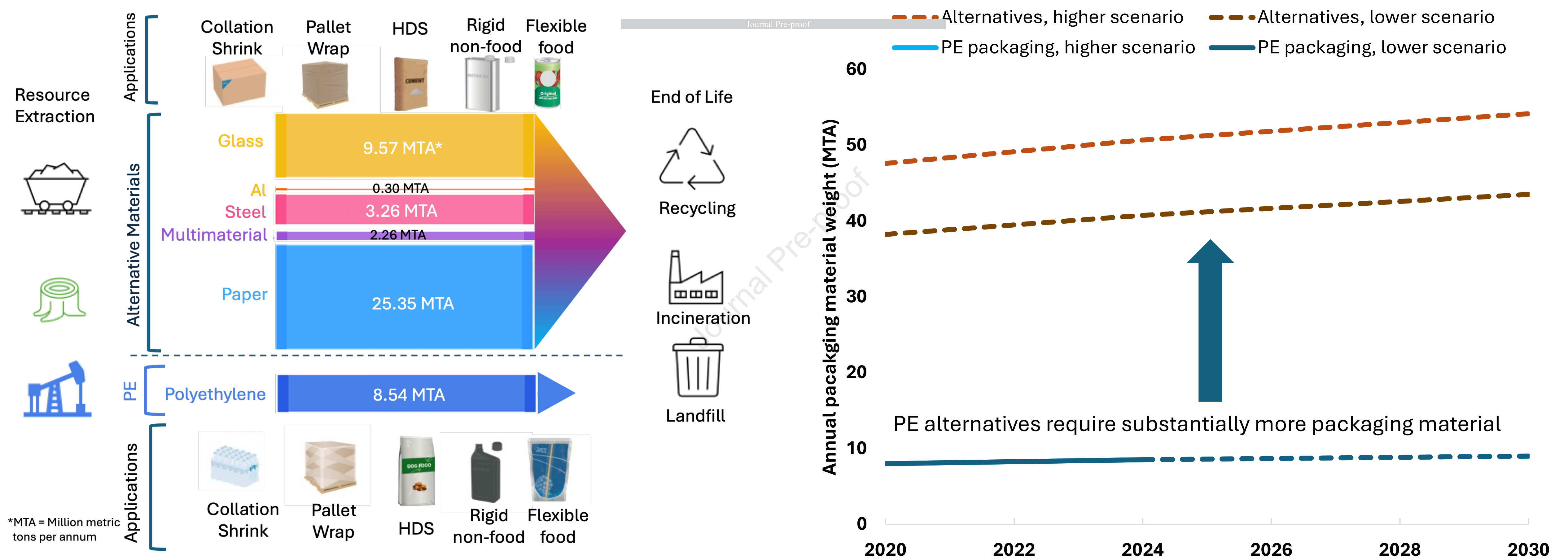

Resource Extraction
Applications
Collation Shrink
Pallet Wrap
HDS
Rigid non-food
Flexible food
Alternative Materials
Glass
9.57 MTA*
Al
0.30 MTA
Steel
3.26 MTA
Multimaterial
2.26 MTA
Paper
25.35 MTA
PE
Polyethylene
8.54 MTA
End of Life
Recycling
Incineration
Landfill
Applications
Collation Shrink
Pallet Wrap
HDS
Rigid non-food
Flexible food
*MTA = Million metric tons per annum
Alternatives, higher scenario
Alternatives, lower scenario
PE packaging, higher scenario
PE packaging, lower scenario
Annual pacakging material weight (MTA)
60
50
40
30
20
10
0
2020
2022
2024
2026
2028
2030
PE alternatives require substantially more packaging material

Environmental Consequences of Replacing Polyethylene Packaging in the United States and Europe

Abstract

Substituting plastic packaging with alternative materials is increasingly promoted as a strategy to reduce environmental burdens and support resource conservation, yet broader trade-offs remain insufficiently understood. This study evaluates potential environmental consequences of replacing polyethylene (PE) packaging with alternatives in the U.S. and Europe using comparative life cycle assessment. Cradle-to-end-of-life impacts were assessed for five major packaging applications using region-specific inventories and midpoint indicators for global warming potential, acidification, eutrophication, water use, land use, and fossil resource use. PE demand and substitution scenarios were projected to 2030 to examine implications for material demand and resource-related impacts. Across most applications and impact categories assessed, PE packaging showed lower potential environmental impacts than paper, glass, and metal alternatives. Substitution could increase packaging mass by up to five to six times and double global warming potential, with increases of 190% in the U.S. and 50% in Europe. These findings indicate that material substitution alone is not necessarily a resource-efficient or environmentally preferable strategy. Packaging decisions and policies should therefore be guided by functionally equivalent, region-specific life cycle data that accounts for burden shifting across resource use, emissions, and end-of-life systems.

Keywords: *equivalent functional unit*; *burden shifting*; *demand forecasting*; *plastic*

List of Abbreviations

Abbreviation	Definition
APET	Amorphous polyethylene terephthalate
BAU	Business-as-usual
B2B	Business-to-business
CAGR	Compound annual growth rate
CB	Corrugated box
CFF	Circular Footprint Formula
CS	Collation shrink
EF	Environmental Footprint
EoL	End-of-life
EPA	Environmental Protection Agency
EPR	Extended Producer Responsibility
EU	European Union
FU	Functional unit
GDP	Gross domestic product
GHG	Greenhouse gas
GWP	Global warming potential
HDS	Heavy-duty sacks
HDPE	High-density polyethylene
ISO	International Organization for Standardization
IW+	Impact World+
KTA	Kilotons per annum
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LDPE	Low-density polyethylene
LLDPE	Linear low-density polyethylene
MTA	Million metric tons per annum
OECD	Organisation for Economic Co-operation and Development
PAST	Packaging Sustainability Tool
PB	Paperboard box
PCR	Post-consumer recycled
PE	Polyethylene
PEF	Product Environmental Footprint
PET	Poly(ethylene terephthalate)
PJ	Petajoule
PP	Polypropylene
PPWR	Packaging and Packaging Waste Regulation
PVC	Polyvinyl chloride
RPC	Reusable Packaging Container
SI	Supporting Information
UNEP	United Nations Environment Programme
U.S.	United States
WFLDB	World Food LCA Database

1. Introduction

Packaging is indispensable to modern economies because it protects products, facilitates efficient distribution, extends shelf life, and can reduce food waste (Lebreton and Andrady, 2019; Wikström et al., 2019). However, increasing concern over mismanaged packaging waste, particularly plastic packaging, and its role in environmental pollution has intensified pressure to transform existing packaging systems. In response, efforts have focused on encouraging material substitution (Dolci et al., 2024; Grosso, 2022), reducing waste pollution (Amadei et al., 2022; Schmaltz et al., 2020), and regulatory intervention (Knoblauch and Mederake, 2021; Tan et al., 2025). Recent policies, including the EU Green Deal (European Commission, 2021), California's SB54 (CalRecycle, 2022), Oregon's Plastic Pollution and Recycling Modernization Act (Circular Action Alliance., 2025), the EU Packaging and Packaging Waste Regulation (PPWR) (Union, 2025), and related Extended Producer Responsibility (EPR) schemes (Mallick et al., 2024; Tumu et al., 2023; Yudison et al., 2026), reflect this shift. Although these initiatives are intended to mitigate environmental impacts, they may also introduce trade-offs and unintended consequences across the packaging life cycle. This context underscores the need for a comprehensive, systems-oriented approach that preserves the essential functions of packaging while addressing environmental burdens and societal expectations across different packaging materials.

Research on single-use plastic packaging has largely focused on its role in packaging applications (Dolci et al., 2024; Geyer et al., 2017), plastic production and associated greenhouse gas emissions (Stegmann et al., 2022), the effect of single-use packaging on coastal environments (Nuojua et al., 2022), the impact of plastic waste littering (Lau et al., 2020), strategies to reduce waste mismanagement (Pottinger et al., 2024), and the environmental consequences of microplastic generation (Martin et al., 2020). However, substantial gaps remain in this literature (Bher and Auras, 2024; United Nations Environment Programme, 2021), including fragmented geographical perspectives (Bher and Auras, 2024), inconsistent environmental characterization methods (Maga et al., 2022), limited transparency in background life cycle inventory (LCI) data (Guo et al., 2025), and simplified assumptions regarding material substitution and end-of-life (EoL) pathways (Nordahl and Scown, 2024; Pellengahr et al., 2023). Moreover, many studies emphasize greenhouse gas emissions while giving less attention to resource use and management and other ecosystem-related impacts.

A robust evaluation of packaging options requires a balanced, systems-based assessment that does not assume material substitution, recyclability, or recycled content will inherently improve environmental impacts (Yudison et al., 2026). The circular economy literature likewise emphasizes that reduction, reuse, and recycling are best understood as strategies for retaining resource value rather than as universally superior solutions (Kirchherr et al., 2017). Packaging alternatives should therefore be assessed on a consistent life cycle basis across the full supply chain, from raw material production and packaging manufacture to distribution, use-phase performance, product protection, losses, and EoL management, because environmental burdens can shift across stages and impact categories (Bher and Auras, 2024; Yudison et al., 2026). Life-cycle thinking is especially important when screening alternative material or feedstock systems, because simplified substitution decisions can overlook hidden burdens and market-mediated effects (Bishop et al., 2025). Such an approach is critical for sustainable resource management and conservation, as decisions focused solely on waste reduction may overlook impacts on fossil fuel use, water, land, and other resource-related pressures, including those associated with replacing lost or damaged products. It is equally important for recycling, where outcomes depend on material efficiency, collection and sorting infrastructure, and the technical feasibility of processing complex packaging formats (Soares et al., 2022).

We previously evaluated the potential environmental impacts of PE packaging, which accounts for two-thirds of packaging plastics in the U.S. and Europe. PE packaging, defined as having at least 50% PE by weight, was compared to alternative packaging solutions, defined as having less than 50% plastics by weight, in the U.S. and European markets in 2023 (Avery et al., 2025; Tacker et al., 2025). The studies covered five PE packaging applications: collation shrink films, pallet stretch wrap, heavy-duty sacks (HDS), rigid non-food containers, and flexible food packaging. However, these studies did not evaluate similarities and differences across regions, including differences in regional life-cycle modeling approaches, particularly end-of-life (EoL) allocation methodologies, or the effects of reuse, post-consumer recycled (PCR) content, and EoL scenarios in the U.S. and Europe. Furthermore, the previous studies (Avery et al., 2025; Tacker et al., 2025) did not investigate how the application of the Circular Footprint Formula (CFF), which is the reference approach under the European Product Environmental Footprint (PEF) methodology, compares with the cut-off allocation approach commonly applied in North American LCA practice. Besides, the findings were limited to the study year and do not capture near-term future developments.

In this work, we expanded previous regional studies by providing an integrated comparison of representative PE packaging systems in the U.S. and Europe within the regional methodological frameworks that currently guide decision-making and policy. The assessment includes 10 midpoint indicators for the U.S. and six for Europe, covering global warming potential (GWP), water scarcity (U.S.) and water use (Europe), fossil resource use, terrestrial acidification, freshwater acidification and eutrophication (U.S.), land transformation and land occupation (U.S.), land use (Europe), mineral resource use (U.S.), and GWP including biogenic carbon uptake (U.S.). This geographically specific comparison addresses an important data gap by evaluating packaging materials across two major high-income markets with substantial packaging consumption.

A particular objective was to evaluate how EoL allocation methods influence comparative packaging conclusions. The European PEF methodology prescribes the CFF, whereas the cut-off approach is more commonly applied in North American LCA practice. Accordingly, the U.S. analysis used the cut-off approach, while the European systems were evaluated using both the CFF and cut-off methods. This harmonized comparison (CFF vs. cut-off) of the European packaging systems allowed us to assess whether the comparative conclusions remained robust when the effects of regional allocation choices were separated from those of packaging design and material selection. This perspective is relevant to inform broader international discussions on plastics and packaging policy. It is particularly relevant to ongoing negotiations toward a United Nations Global Plastics Instrument, where the principle of common but differentiated responsibilities (CBDR), which takes into account national circumstances and capabilities (UNEP, 2022a; Wang, 2025), remains an important consideration. Because the U.S. and Europe represent major high-income markets with substantial packaging consumption, integrating both regions in a common assessment helps address an important data gap. The results can support evidence-based discussions on material substitution, resource efficiency, and trade-offs in life-cycle GHGs, eutrophying and acidifying emissions as countries continue negotiating global approaches to plastic pollution and sustainable packaging systems.

The analysis was also expanded to include selected case-specific scenarios for reuse, post-consumer recycled content, and EoL management. In addition, annualized midpoint environmental impacts were estimated for 2020–2024, projected to 2030, and extrapolated to 2050 under a business-as-usual (BAU) scenario using the best available estimates of current and future PE market volumes. Together, these contributions provide a more robust basis for evaluating material substitution, resource efficiency, trade-offs in life cycle GHGs, eutrophying and acidifying emissions, and future packaging policy across the two regions.

2. Materials and methods

2.1. Goal, Scope, Functional Unit, Life Cycle Inventory, and Life Cycle Impact Assessment

Two attributional life cycle assessments (LCAs), conformant with ISO 14040/14044 (more information on the critical review process in Section S3), were conducted to compare the cradle-to-EoL impacts of PE packaging *vs*. paper, glass, aluminum, and steel packaging in the U.S. and European markets in 2024, and to update the 2023 data estimated in our previous work (Avery et al., 2025; Tacker et al., 2025). Five packaging applications were covered: collation shrink, pallet stretch wrap, HDS, rigid non-food containers, and flexible food packaging, across 13 U.S. (**Table S1**) and 17 European (**Table S2**) packaged products. The scope excluded the packaged product and use-phase effects (breakage, product loss, shelf life). Package definitions, functional units, and masses were based on industry-representative configurations previously documented for 2023 (Avery et al., 2025; Tacker et al., 2025), updated from ecoinvent 3.8 to 3.10, and fully described in Section S1 of the Supporting Information (SI) available online; **Tables S1** and **S2**. Packaging systems were selected to represent commercially available solutions currently used for the same packaging application and providing equivalent technical functionality. Functional equivalence was assumed as the compared packaging samples are expected to provide comparable performance with respect to product protection, containment, handling, storage, distribution and consumer use under normal commercial conditions. Consequently, the comparison represents equivalent packaging systems from the US and European markets rather than hypothetical substitutions based solely on packaging mass. While a small number of samples were collected from retail stores, the sample set was considered representative of packaging sold through mainstream channels in 2023-2024.

For the U.S., LCI was structured into raw material, manufacturing, transportation, and EoL stages. Trayak Inc. collected primary data on dimensions and mass from physical samples or specification sheets (typically 1–3 per format), using mass-per-capacity ratios where capacities varied. Secondary and tertiary packaging masses were calculated from dimensions and reference material weights. Secondary data came primarily from ecoinvent 3.10 (cut-off and unit processes where available), supplemented by the U.S. LCI, WFLDB, Agri-footprint, Agribalyse, literature, industry LCAs, supplier data, and Trayak Inc.-specific processes. The U.S. EoL disposition and recycling rates were based on the U.S. EPA data, with the ecoinvent grid adjusted to the U.S. average. **Table S3** provides the LCI used for modeling in the U.S. scenarios.

For Europe, LCI followed the same four stages and was compiled by Circular Analytics TK GmbH based on direct measurements of market samples and specification sheets, or, when absent, physical identification and empirical estimation of components. Models used ecoinvent 3.10 with European regionalization and were aligned with the product environment footprint (PEF) guidance for transport and the Circular Footprint Formula (CFF) for recycled content and EoL. Unless specified, 0% PCR was assumed for most materials; metals, corrugated board, and glass were modeled with recycled content, whereas PE, aluminum, paper, and solid board typically were not. EoL rates were obtained from Eurostat. **Table S4** provides the LCI used for each modeling in the EU scenarios.

U.S. comparisons were modeled with EcoImpact-COMPASS. European systems were modeled in openLCA (ecoinvent 3.10; EF 3.1 method via openLCA LCIA Methods 2.4.1) and implemented in the Excel-based PAST tool. Ten single-midpoint indicators were evaluated for the U.S.; specific GWP, water scarcity, fossil energy use, freshwater acidification and eutrophication, land transformation and occupation, mineral resource use, and GWP with CO_2 uptake. Six single-midpoint indicators for Europe were evaluated based on the Environmental Footprint (EF) 3.1: GWP, water use, fossil resource, acidification, eutrophication, and land use, using the CFF and cut-off methodology. Additional single-midpoint indicators were reported for the EU according to Impact World+. **Table S5** shows a detailed description of each indicator. Midpoint indicators were chosen over endpoint indicators to enhance clarity and robustness (Bare et al., 2000), and comparative conclusions were interpreted using a 10% difference as the threshold for meaningfully identifying higher or lower impacts, consistent with common practice in LCA when comparing midpoint indicators (Klöpffer and Grahl, 2009). Complementary detailed information regarding the goal and scope, as well as boundary conditions, is provided in Section S1 of the SI.

2.2. Estimated PE demand between 2020 and 2050

Thirteen packaged products were assessed in the US. Seventeen packaged products were evaluated in Europe (**Tables S1 and S2**) covering approximately two-thirds of the plastic packaging market in 2024 (3.07 million metric tons per annum (MTA) in the U.S. and 5.47 MTA in Europe), **Figure 1 A** and **B**.

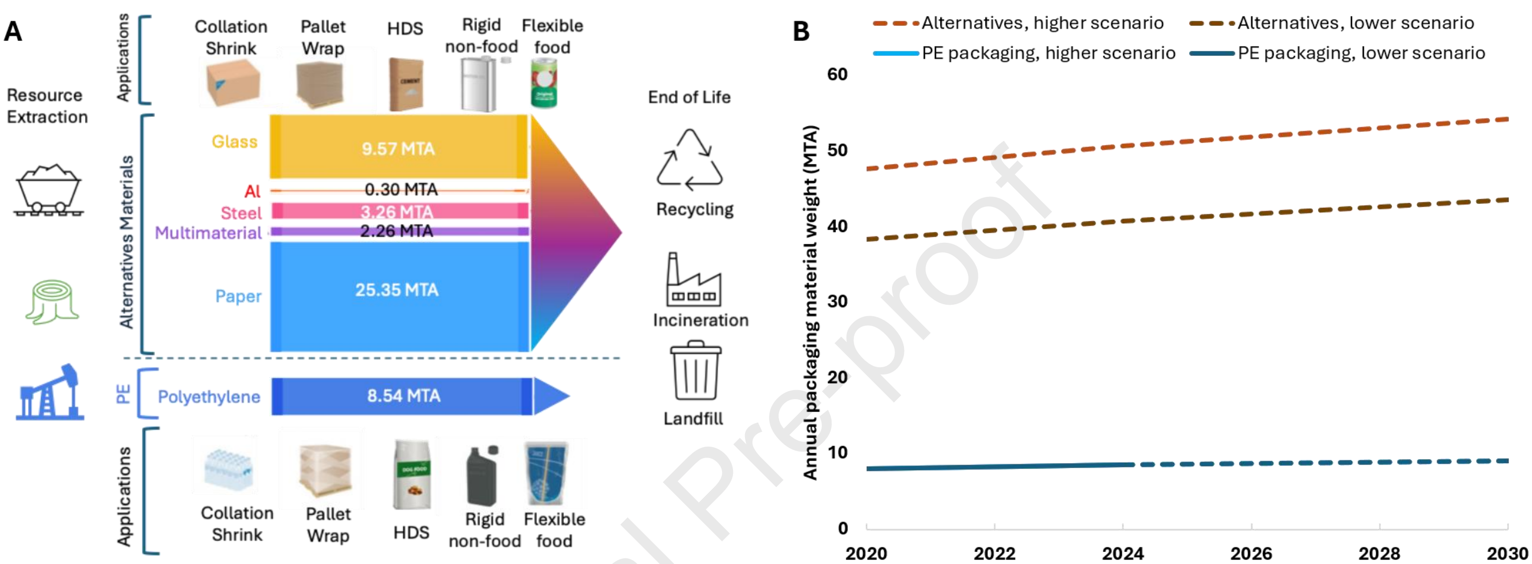

Figure 1. The U.S. and Europe's consumption of Polyethylene and alternative materials from 2020 to 2030. (A) Volumes of polyethylene and alternative materials minimum replacement estimation, Paper, Multimaterial, Steel, Aluminum, and Glass for the 5 assessed Polyethylene Applications, Pallet Wrap, Collation Shrink, Heavy Duty Sack (HDS), Rigid Non-Food Containers, and Flexible Food Packaging, in million metric tons in 2024. B) Total predicted consumption of Polyethylene and Alternatives until 2024. Dashed Lines represent the modeled forecast for consumption after 2024 and the estimated demand for PE alternatives (2020-2030). Note: PE packaging higher- and lower-scenario trajectories diverge after 2030, so the solid and dashed lines overlap until then.

The demand over the decade (2020-2030) was calculated based primarily on Townsend (2024) (Townsend_Solutions, 2024), supplemented by AMI (2018, 2024) (Applied Market Information Ltd. (AMI), 2024, 2018), Freedonia 2023 (Freedonia Group, 2020), Smithers (2019, 2024) (Forster et al., 2021; Pira, 2024), EuroMonitor (2023) (Euromonitor_International, 2023), which can be suitable for historical, current, and short-term PE packaging demand and further described in Section S2 (**Fig. S1- S4** and **Table S6**). Projecting demand to 2030 under a BAU scenario is reasonable, as the development and full implementation of new packaging systems typically takes between 18 and 60 months from conception to deployment.

For the medium- to long-term (2030-2050), we developed BAU extrapolations to provide an initial assessment of potential future outcomes. These extrapolated scenarios should be interpreted with caution, but they can still serve as baseline cases for assessing future improvements when considering other models. The lower PE demand scenario, representing a conservative demand profile, was based on Chemical Market Analytics (2024) (CMA, 2024), and the higher PE demand, we based the scenario on OECD (2024) (with data derived from (Geyer et al., 2017; OECD, 2022; Ryberg et al., 2019)). Additional information on PE estimations in the U.S. and Europe can be found in Section S2 of the SI.

2.3. Estimated PE packaging and substitutes

We used LCI data (see previous sections and SI) and PE packaging demand to estimate the annual impacts of PE packaging. The weight ratios of the mix of alternative packaging material formats (paper, paper multi-material, glass, and metals) to PE from the comparative packaging LCI data were used in this analysis, assuming the alternatives can substitute PE packaging in the U.S. and Europe based on the assessed functional units (**Tables S7 - S8**). We used the annual PE demand and the substitutes-to-PE weight ratios to estimate the annual weights of required PE substitutes and their corresponding potential annual environmental impacts across six impact categories, including emissions and resource-use-related impacts (**Tables S27-S32**).

3. Results & Discussion

3.1. LCA of PE Packaging vs. Alternatives

In both the U.S. and Europe, single-use PE packaging generally showed lower environmental impacts than alternatives (glass, paper, metal) across most categories studied such as GWP (84% U.S., 68% Europe (i.e., the cases where PE has a more than 10% lower environmental impact than the alternative), water scarcity (84% U.S.) and water use (64% Europe), fossil resource use (74% U.S., 45% Europe), terrestrial and freshwater acidification (79% U.S.), acidification (82% Europe), freshwater eutrophication (100% U.S.), eutrophication (95% Europe), land transformation (84% U.S.), land occupation (95% U.S.), land use (95% Europe), mineral resource use (79% U.S.), and GWP with biogenic carbon uptake (79% US) (**Figure 2**). The results varied by application, indicator, and region, with the summary below highlighting key similarities and differences between the U.S. and Europe packaging applications studied, along with relevant considerations. Detailed environmental impacts by life-cycle stage are provided in **Tables S9-S18** (U.S.) and **Tables S19-S24** (Europe).

Collation Shrink: In the U.S., collation PE shrink film wraps (for water bottles and body wash) exhibited lower impacts than corrugated and paperboard boxes across all the ten potential environmental indicators studied. In the EU, PE shrink wrap for water bottles had higher impacts in five of six categories compared to a lightweight virgin Kraft paper band, whereas for cans it showed lower impacts than corrugated board wraps across all categories, reflecting the markedly lower material intensity of the paper band versus the corrugated board. The difference between the U.S. and EU in the collation shrink for water bottles can be attributed to the EU's lightweight design, consisting only of a low-weight stretchable Kraft paper band rather than heavier corrugated board (**Tables S1 and S2**). The PPWR proposes to restrict by 2030 the use of collation films and shrink wraps at the point of sale for grouped goods such as bottles and cans. However, alternative packaging solutions do not always offer lower potential environmental impacts, making the transition potentially less environmentally beneficial than intended (Union, 2025), as in the case of EU cans (**Figure 2 B**).

Pallet Wrap: PE-stretch wrap demonstrated lower potential environmental impacts than paper or reusable pallet wrap across all indicators for both the U.S. and the EU, except for fossil resource use in the EU, driven mainly by the material and manufacturing phases due to the embodied fossil carbon and the raw material extraction, refining, and manufacturing processes (**Section S1** and **Table S20**). Although pallet stretch wrap is often cited as a packaging waste concern, the waste is primarily generated in warehouses and other B2B environments where centralized collection systems facilitate recovery, creating a strong opportunity for densification technologies to facilitate improved EoL management (Oloruntobi et al., 2023; Stefanini et al., 2024; Zeilerbauer et al., 2024).

HDS: For the U.S., PE HDS had higher impacts than paper-multimaterial sacks in six out of ten indicators for dog food and eight out of ten for cement, but showed lower impacts for eutrophication and land occupation. The EU results were quite similar for fertilizer and cement, with higher impacts for PE HDS in GWP and fossil resource use, but lower impacts for acidification, eutrophication, and land use. However, for packaged products with high environmental impact potential, research has shown that accounting for potential product losses resulting from packaging-related performance differences across the supply chain are crucial (Bher and Auras, 2024; Yudison et al., 2026).

Rigid Non-Food Packaging: PE bottles (cosmetics, vitamins, paint, motor oil) exhibited lower potential environmental impacts across all impact categories than glass or metal in both the U.S. and EU. The only exceptions were land use for one body cream comparison, and indeterminate results (within ±10%) for fossil resource use in aluminum and water use in glass for soap and vitamin packaging in the EU. Indeterminate results were also observed in the U.S. regarding fossil energy use for cosmetics packaging and land occupation associated with paint packaging. For PE, glass, and aluminum, material production was the dominant contributor to environmental impacts.

Flexible Food Packaging: In the U.S., PE pouches often showed the lowest impacts (e.g., candy, sauce), though paper performed better on two out of ten indicators for juice and six out of ten indicators for spices. In the EU, PE outperformed alternatives for cocoa and instant coffee, though paper bags for salt and sugar had lower impacts in four out of six impact categories, and one paper-based frozen food packaging showed lower impacts in GWP, water use, and fossil resource use, with indeterminate results for acidification. Although packaging often receives significant attention, extensive research recommends that for foods with high environmental impacts, such as dairy and meat, packaging design should prioritize minimizing food waste (Bher and Auras, 2024; UNEP, 2022b). Functional equivalence should also be considered, meaning how much of an alternative material is needed to provide equivalent protection for a food item (Yudison et al., 2026).

A - U.S. IW+ & Cut-off

Single use alternatives comparative scenarios for the U.S.	Collation Shrink		Pallet Wrap	Heavy Duty Sacks		Rigid Non-food bottles					Flexible food packaging											All Applications		
	Water bottles	Body Wash		Dog food	Cement	Cosmetic	Shampoo	Paint	Motor oil		Juice			Candy		Sauce		Spices				PE lower impact	±10% margin	PE higher impact
GWP, kg CO_2-eq	P1	P2	P3	M1	M2	G1	S1	S2	A1		M3	A2	G2	P4	S3	G3	S4	P5	G4	S5		16/19 (84%)	0/19 (0%)	3/19 (16%)
Water scarcity, m³ world-eq	P1	P2	P3	M1	M2	G1	S1	S2	A1		M3	A2	G2	P4	S3	G3	S4	P5	G4	S5		16/19 (84%)	0/19 (0%)	3/19 (16%)
Fossil Energy Use, MJ deprived	P1	P2	P3	M1	M2	G1	S1	S2	A1		M3	A2	G2	P4	S3	G3	S4	P5	G4	S5		14/19 (74%)	2/19 (11%)	3/19 (16%)
Terrestrial acidification, kg SO_2 eq	P1	P2	P3	M1	M2	G1	S1	S2	A1		M3	A2	G2	P4	S3	G3	S4	P5	G4	S5		15/19 (79%)	2/19 (11%)	2/19 (11%)
Freshwater acidification, kg SO_2 eq	P1	P2	P3	M1	M2	G1	S1	S2	A1		M3	A2	G2	P4	S3	G3	S4	P5	G4	S5		15/19 (79%)	2/19 (11%)	2/19 (11%)
Freshwater eutrophication, kg PO_4 eq	P1	P2	P3	M1	M2	G1	S1	S2	A1		M3	A2	G2	P4	S3	G3	S4	P5	G4	S5		19/19 (100%)	0/19 (0%)	0/19 (0%)
Land transformation, m² y arable	P1	P2	P3	M1	M2	G1	S1	S2	A1		M3	A2	G2	P4	S3	G3	S4	P5	G4	S5		16/19 (84%)	0/19 (0%)	3/19 (16%)
Land Occupation, m² y arable	P1	P2	P3	M1	M2	G1	S1	S2	A1		M3	A2	G2	P4	S3	G3	S4	P5	G4	S5		18/19 (84%)	1/19 (5%)	0/19 (0%)
Mineral resources Use, kg deprived	P1	P2	P3	M1	M2	G1	S1	S2	A1		M3	A2	G2	P4	S3	G3	S4	P5	G4	S5		15/19 (79%)	1/19 (5%)	3/19 (16%)
GWP, with CO_2 uptake, kg CO_2-eq	P1	P2	P3	M1	M2	G1	S1	S2	A1		M3	A2	G2	P4	S3	G3	S4	P5	G4	S5		15/19 (79%)	1/19 (5%)	3/19 (16%)

B - EU - EF3.1 & CFF

Single use alternatives comparative scenarios for the EU	Collation Shrink		Pallet Wrap	Heavy Duty Sacks		Rigid non-food packaging					Flexible Food Packaging												All Applications		
	Water bottles	Cans		Cement	Fertilizer	Body cream		Soap	Vitamins	Motor oil	Apples	Cocoa		Frozen foods		Instant coffee		Produce bags	Potatoes	Salt		Sugar	PE lower impact	±10% margin	PE higher impact
GWP, kg CO_2-eq	P1	P2	P3	M1	P4	G1	A1	G2	G3	S1	P5	M2	S2	M3	M4	G4	S3	P6	M5	P7	M6	P8	15/22 (68%)	1/22 (5%)	6/22 (27%)
Water use, m³ world eq-deprived	P1	P2	P3	M1	P4	G1	A1	G2	G3	S1	P5	M2	S2	M3	M4	G4	S3	P6	M5	P7	M6	P8	14/22 (64%)	3/22 (14%)	5/22 (23%)
Fossil resource use, MJ	P1	P2	P3	M1	P4	G1	A1	G2	G3	S1	P5	M2	S2	M3	M4	G4	S3	P6	M5	P7	M6	P8	10/22 (45%)	2/22 (9%)	10/22 (45%)
Acidification, mol H⁺ eq	P1	P2	P3	M1	P4	G1	A1	G2	G3	S1	P5	M2	S2	M3	M4	G4	S3	P6	M5	P7	M6	P8	18/22 (82%)	1/22 (5%)	3/22 (14%)
Eutrophication, kg P-eq	P1	P2	P3	M1	P4	G1	A1	G2	G3	S1	P5	M2	S2	M3	M4	G4	S3	P6	M5	P7	M6	P8	21/22 (95%)	0/22 (0%)	1/22 (5%)
Land use, no dimension	P1	P2	P3	M1	P4	G1	A1	G2	G3	S1	P5	M2	S2	M3	M4	G4	S3	P6	M5	P7	M6	P8	21/22 (95%)	0/22 (0%)	1/22 (5%)

C - EU- EF3.1 & Cut-off

Single use alternatives comparative scenarios for the EU	Collation Shrink		Pallet Wrap	Heavy Duty Sacks		Rigid non-food packaging					Flexible Food Packaging												All Applications		
	Water bottles	Cans		Cement	Fertilizer	Body cream		Soap	Vitamins	Motor oil	Apples	Cocoa		Frozen foods		Instant coffee		Produce bags	Potatoes	Salt		Sugar	PE lower impact	±10% margin	PE higher impact
GWP, kg CO_2-eq	P1	P2	P3	M1	P4	G1	A1	G2	G3	S1	P5	M2	S2	M3	M4	G4	S3	P6	M5	P7	M6	P8	11/22 (50%)	3/22 (14%)	8/22 (36%)
Water use, m³ world eq-deprived	P1	P2	P3	M1	P4	G1	A1	G2	G3	S1	P5	M2	S2	M3	M4	G4	S3	P6	M5	P7	M6	P8	10/22 (45%)	3/22 (14%)	9/22 (41%)
Fossil resource use, MJ	P1	P2	P3	M1	P4	G1	A1	G2	G3	S1	P5	M2	S2	M3	M4	G4	S3	P6	M5	P7	M6	P8	10/22 (45%)	1/22 (5%)	11/22 (50%)
Acidification, mol H⁺ eq	P1	P2	P3	M1	P4	G1	A1	G2	G3	S1	P5	M2	S2	M3	M4	G4	S3	P6	M5	P7	M6	P8	17/22 (77%)	2/22 (9%)	3/22 (14%)
Eutrophication, kg P-eq	P1	P2	P3	M1	P4	G1	A1	G2	G3	S1	P5	M2	S2	M3	M4	G4	S3	P6	M5	P7	M6	P8	20/22 (91%)	0/22 (0%)	2/22 (9%)
Land use, no dimension	P1	P2	P3	M1	P4	G1	A1	G2	G3	S1	P5	M2	S2	M3	M4	G4	S3	P6	M5	P7	M6	P8	21/22 (95%)	0/22 (0%)	1/22 (5%)

D- EU- IW+ & Cut-off

Single use alternatives comparative scenarios for the EU	Collation Shrink		Pallet Wrap	Heavy Duty Sacks		Rigid non-food packaging					Flexible Food Packaging												All Applications		
	Water bottles	Cans		Cement	Fertilizer	Body cream		Soap	Vitamins	Motor oil	Apples	Cocoa		Frozen foods		Instant coffee		Produce bags	Potatoes	Salt		Sugar	PE lower impact	±10% margin	PE higher impact
GWP, kg CO_2-eq	P1	P2	P3	M1	P4	G1	A1	G2	G3	S1	P5	M2	S2	M3	M4	G4	S3	P6	M5	P7	M6	P8	11/22 (50%)	3/22 (14%)	8/22 (36%)
Water scarcity, m³ world-eq	P1	P2	P3	M1	P4	G1	A1	G2	G3	S1	P5	M2	S2	M3	M4	G4	S3	P6	M5	P7	M6	P8	9/22 (41%)	4/22 (18%)	9/22 (41%)
Fossil Energy Use, MJ deprived	P1	P2	P3	M1	P4	G1	A1	G2	G3	S1	P5	M2	S2	M3	M4	G4	S3	P6	M5	P7	M6	P8	9/22 (41%)	1/22 (5%)	12/22 (55%)
Terrestrial acidification, kg SO_2 eq	P1	P2	P3	M1	P4	G1	A1	G2	G3	S1	P5	M2	S2	M3	M4	G4	S3	P6	M5	P7	M6	P8	16/22 (73%)	3/22 (18%)	3/22 (18%)
Freshwater acidification, kg SO_2 eq	P1	P2	P3	M1	P4	G1	A1	G2	G3	S1	P5	M2	S2	M3	M4	G4	S3	P6	M5	P7	M6	P8	16/22 (73%)	1/22 (5%)	5/22 (23%)
Freshwater eutrophication, kg PO_4 eq	P1	P2	P3	M1	P4	G1	A1	G2	G3	S1	P5	M2	S2	M3	M4	G4	S3	P6	M5	P7	M6	P8	22/22 (100%)	0/22 (0%)	0/22 (0%)
Land transformation, m² y arable	P1	P2	P3	M1	P4	G1	A1	G2	G3	S1	P5	M2	S2	M3	M4	G4	S3	P6	M5	P7	M6	P8	21/22 (95%)	0/22 (0%)	1/22 (5%)
Land Occupation, m² y arable	P1	P2	P3	M1	P4	G1	A1	G2	G3	S1	P5	M2	S2	M3	M4	G4	S3	P6	M5	P7	M6	P8	20/22 (91%)	0/22 (0%)	2/22 (9%)

Note:	PE Comparison Material	A	Aluminium	G	Glass	M	Multimaterial Paper	P	Paper	S	Steel	PE lower impact	PE Similar impact	PE higher impact

Figure 2. **Summary of life cycle impact assessment results for the packaging product category**: (A) U.S. main packaging assessed with IW+ midpoint indicators and cut-off EoL modeling; (B) EU main packaging assessed with EF3.1 midpoint indicators and CFF EoL modeling; (C) EU main packaging assessed with EF3.1 midpoint indicators and cut-off EoL modeling; and (D) EU main packaging assessed with selected IW+ midpoint indicators and cut-off EoL modeling. White cells indicate PE is >10% lower than the alternative, orange cells indicate a difference within ±10%, and black cells indicate PE is >10% higher than the alternative. Note: main packaging applications: collation shrink films, stretch wrap for pallets, heavy-duty sacks (HDS), rigid non-food containers, and flexible food packaging. Label notations, for example, P1: corrugated box (CB) for the U.S. and P1: paper wrap with corrugated board carrier for the EU, are detailed in **Tables S1** and **S2** in the Supporting Information, respectively

For the EU, EoL impacts were calculated using the CFF, in line with European Commission recommendations. To test the influence of allocation choice, the cut-off approach (**Figure 2 C**) and the selective midpoint indicators for the EU – IW+ & cut-off approach (**Figure 2 D**), as in the U.S., were applied as a sensitivity analysis. Across most applications and impact categories, the relative ranking of packaging alternatives changed little between methods. Although absolute values varied across indicators, particularly GWP and water use, the direction and overall magnitude of the differences between PE and alternative materials remained consistent. This indicates that the comparative conclusions are robust to the choice of EoL allocation method (**Figure 2B** and **C**). Similar patterns were observed across other impact categories, including water use, acidification, eutrophication, and land use, although some selective trade-offs were identified for the specific midpoint indicator methods (**Figure 2 B** and **C**). The comparison between the CFF and cut-off according to the EF3.1+ methods further shows that EoL allocation has only a limited influence on the comparative results of this study. When comparing the EU EF3.1 and IW+ under cut-off allocation, trends remain consistent (**Figure 2 C** and **D**). While allocation choices affect absolute impacts, especially for recycling-sensitive indicators, the relative performance of PE versus alternative materials is driven mainly by material production, mass requirements, and processing. In other words, material efficiency is often the dominant factor shaping the life-cycle results of packaging systems. Some alternatives, particularly paper and multi-material structures, can reduce fossil resource use, but this does not necessarily translate into lower impacts across other categories. Overall, the findings suggest that in the assessed comparisons, replacing single-use PE packaging with alternative single-use materials, such as paper, glass, or metal, often increases GWP, consistent with previous studies (Meng et al., 2024).

The PPWR seeks to support a more circular packaging economy through packaging waste reduction targets of 5% by 2030, 10% by 2035, and 15% by 2040 relative to 2018, together with requirements for recyclability, recycled content incorporation, and adoption of reuse and refill systems. The regulation also restricts selected single-use packaging applications, including some plastic packaging formats for fresh produce, while allowing exemptions for sensitive food-contact uses. However, the present results suggest that some of these measures may not consistently align with the regulation's intended environmental objectives. In particular, replacing single-use PE packaging with alternative single-use materials may increase impacts across several categories, suggesting that differences between commonly held assumptions about packaging materials and the modeled outcomes observed in this study highlight the importance of application-specific life-cycle evaluation (Miller, 2020).

3.2. Reuse, Post Consumer Recyclate (PCR), and End-of-Life (EoL) for Single-Use Plastics: US–EU Parallels, Gaps, and Lessons

Reuse: A significant challenge for the U.S. and Europe lies in transportation distances, which can limit the effectiveness of reuse initiatives, as well as in transport modes, the number of reuse cycles, and additional processes such as washing (Circular Place, n.d.; Mahmoudi and Parviziomran, 2020). As global discussions intensify around reuse as a key strategy for reducing single-use plastic packaging, reuse systems are increasingly being implemented worldwide (Mahmoudi and Parviziomran, 2020). Each case must be evaluated individually. For instance, this study shows that reusable crates for bottled water distribution in Europe provide no significant advantage (within a ±10% margin of error) or only marginal environmental benefits when crates achieve at least 70 rotations and transport distances remain below 200 km per rotation. In practice, however, transport distances are typically around 500 km for fast-moving consumer goods in larger European countries such as Germany and France, and the PPWR Art. 29 assumes 1000 km as the standard distribution distance between two economic operators in Europe (Kauertz and Drescher, 2025; Union, 2025). Affected impact categories include fossil resource use, water consumption, and eutrophication (**Figure 3 A**). Similar trends emerge with multi-use pallet wrap, which shows lower potential environmental impacts when used for 100 rotations or more at distances under 200 km per rotation. Consequently, transporting reusable packaging over a distance of 320 km (e.g., Paris to Dijon) may increase environmental impacts, reducing the net benefit of reuse systems. Different numbers of rotations or transport modes, such as train transport, affect the distances reported (**Figure 3 A** and **B**). In the U.S., similar trends were assessed for multi-use crates; a round trip of 400 km had higher potential environmental impacts (**Figure 3 E**). For multi-use pallet wrap, an effective use rate of 31.7% and distances below 300 km resulted in lower environmental impacts for some indicators (**Figure 3 F**). However, reusable packaging systems may cause greater environmental impacts when transport distances exceed 455 km, such as between Detroit and Chicago, unless transportation-related environmental impacts are reduced (Avery et al., 2027; González Romero et al., 2024).

PCR content incorporation: There is growing discussion about the societal benefits of recycling. Analysis of midpoint indicators for packaging formats such as paper wrap and stretch film (**Figure 3 C** and **G**) and cosmetics (**Figure 3 D** and **H**) in both Europe and the U.S. consistently demonstrates lower potential environmental impacts as the share of PCR content increases. Incorporating recycled materials typically reduces potential environmental impacts across several impact categories, although this depends on the midpoint indicator (**Figure 3 C**, **D**, **E**, **H**). Despite this, the overall reduction of potential environmental impacts remains evident (Avery et al., 2027; Muzata et al., 2024; Saldaña-Pierard et al., 2025). However, the declared recycled content may vary substantially depending on the chain-of-custody model and allocation method, used, meaning that PCR claims require transparent and harmonized calculation rules to ensure that reported recycled content reflects the actual material incorporated into products (Caraceni et al., 2024).

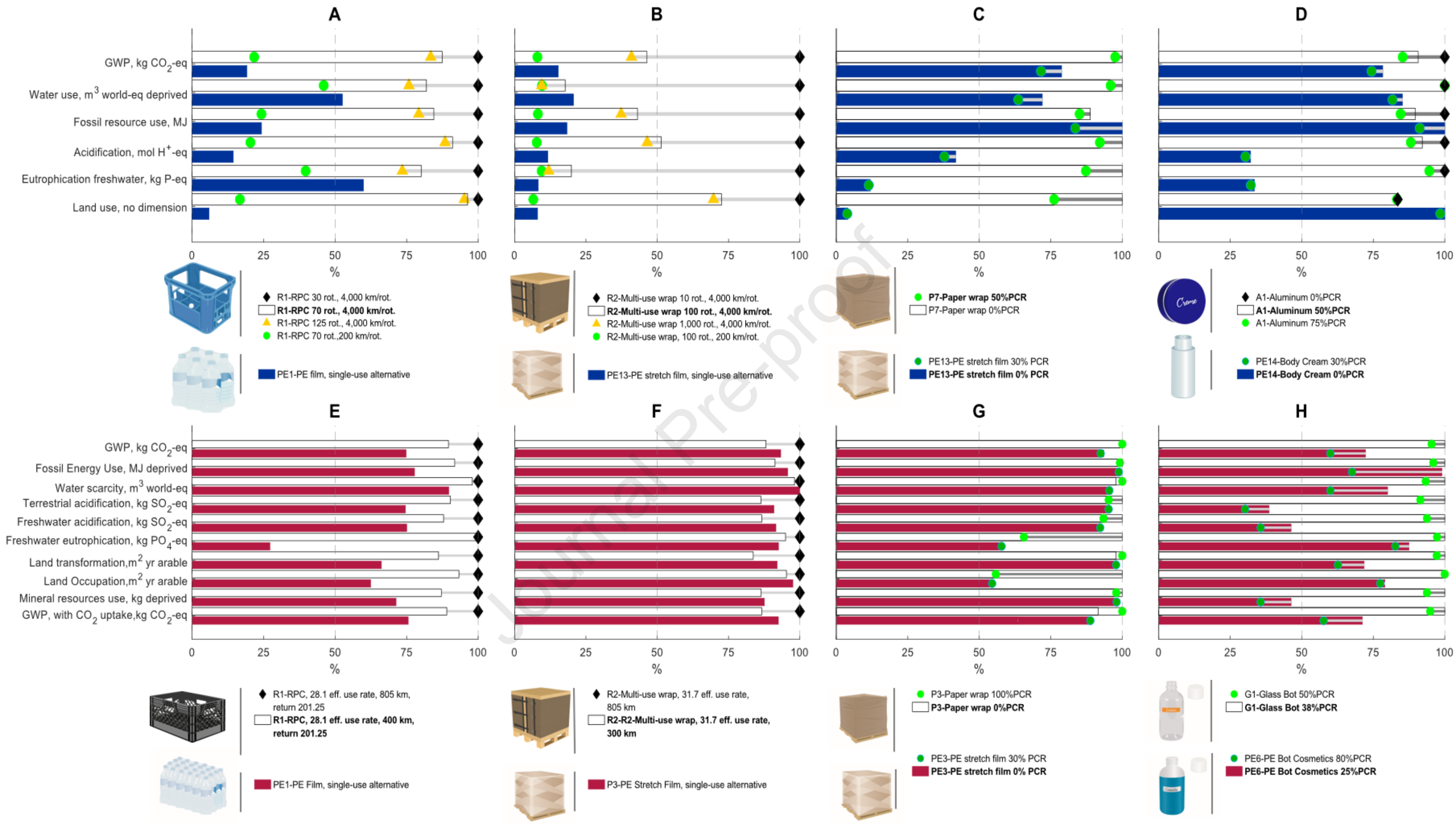

Figure 3. **Impact of different LCA scenario analyses in Europe and the U.S.**: (**A** and **E**) reuse of multi-use crate and collation shrink in Europe (top and blue) – baseline 70 rotations and 4,000 km per rotation – and U.S. (bottom and red); (**B** and **F**) reuse of multi-use pallet wrap and LLDPE stretch film in Europe (top and blue) – baseline 100 rotations and 4,000 km per rotation – and U.S. (bottom and red); (**C** and **G**) increase of PCR on paper wrap and LLDPE stretch film in Europe (top and blue) and U.S. (bottom and red); (**D** and **H**) increase of PCR in cosmetics in Europe (top and blue) and U.S. (bottom and red). RPC means Reusable Plastic Container. **Note: Baseline systems are indicated in bold**.

Recycling at EoL: The environmental impact of increasing recycling rates varies widely by material and impact category. In the U.S., increasing EoL recycling of PE stretch film from 13% to 21% yields results within the margin of error; for instance, GWP drops by just 1% (**Figure 4**). For paper wrap, raising the EoL recycling rate from 21% to 81% yields modest reductions: a 3% decrease in GWP and freshwater eutrophication, and a 5% reduction in GWP with CO_2 uptake, with no significant changes in other indicators (**Table S29**). These limited benefits are primarily attributed to the cut-off methodology, which excludes EoL recycling operations and subsequent credits and burdens from the system boundaries. However, landfilling paper in the U.S. significantly impacts results due to methane emissions from paper decomposition (Anshassi et al., 2021).

In Europe, changes in recycling rates can led to trade-offs across impact categories rather than uniform environmental benefits. These outcomes reflect the balance between the avoided production of virgin material and the additional burdens associated with collection, sorting, reprocessing, and material losses. For example, increasing the recycling rate of PE stretch film from 41% to 70% reduces GWP impacts by up to 15% (**Figure 4**), but increases eutrophication by up to 21% (**Table S25**). The paper wrap shows more mixed outcomes. Lowering the paper recycling rate from 82.5% to 50% can reduce fossil resource use by 10% and water consumption by 15%, but increases land use by 23% (**Table S20**). This result indicates that higher paper recycling can reduce demand for virgin fiber and the associated land occupation, while also increasing burdens related to fiber recovery and reprocessing. In contrast, increasing the recycling rate of the aluminum body cream packaging from 76% to 82.5% reduces GWP by 14%, acidification by 11%, and fossil resource use by 15% (**Table S25**). The more consistently favorable outcome for aluminum likely reflects the magnitude of environmental impacts avoided in the assessed midpoint indicators when secondary aluminum displaces primary aluminum production.

These results demonstrate that recycling rate alone is not an adequate indicator of overall environmental impact. Decision-makers should therefore avoid assuming that maximizing recycling will improve every impact category. Instead, recycling targets should be evaluated by material type and across multiple environmental indicators, with particular attention to the magnitude of avoided virgin production, recycling process efficiency, material quality losses, and the potential for shifting burdens among GWP, eutrophication, water use/scarcity, land use, and resource depletion. For the European systems assessed here, increasing recycling appears especially beneficial when it displaces highly impact-intensive virgin production, as observed for aluminum, whereas the benefits are more category-dependent for PE and paper.

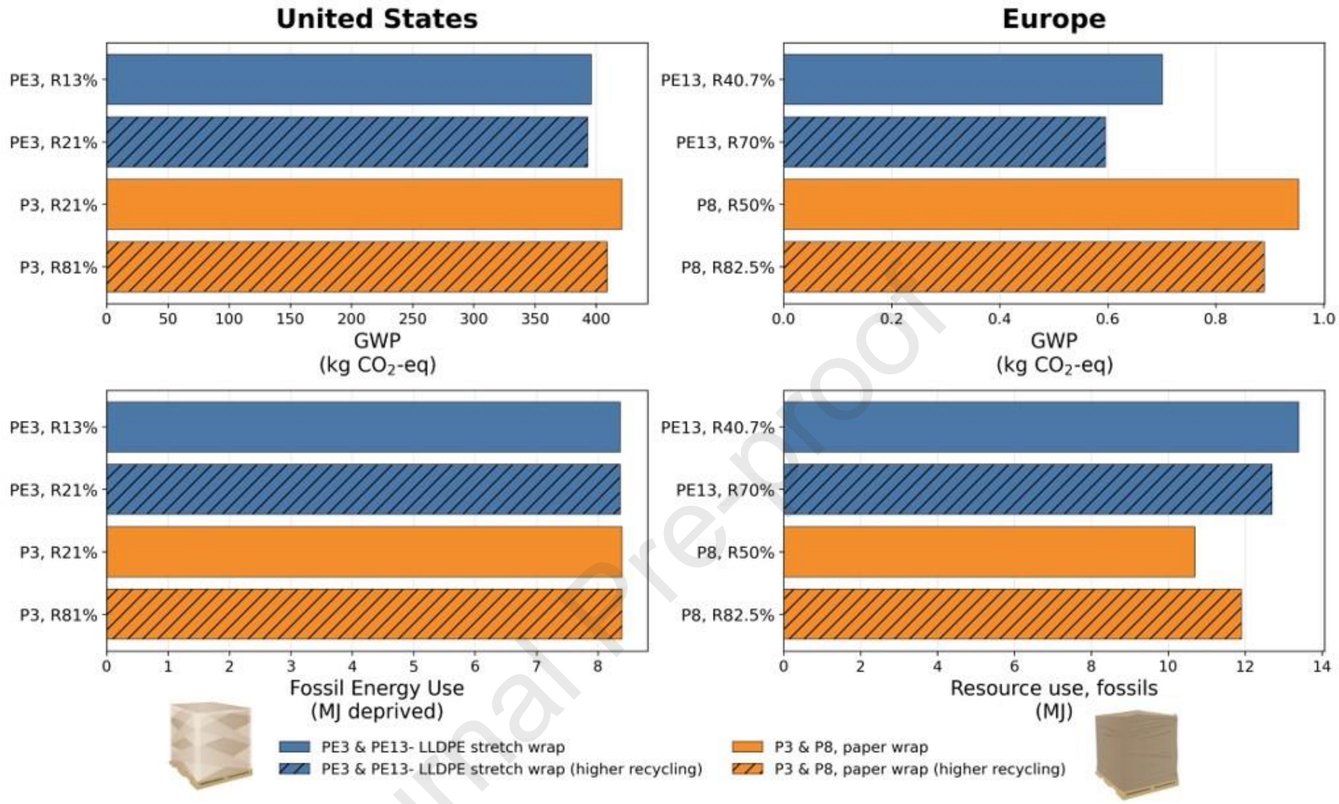

Figure 4. **Comparison of selected midpoint environmental indicators for stretch-film and paper-wrap packaging systems in the U.S. and Europe**. Left: U.S. results for GWP and fossil energy use of PE stretch film and paper wrap at different EoL recycling rates. Right: European results for GWP and fossil resource use. Colors indicate material systems, and hatch patterns indicate recycling-rate scenarios within each material group. Values differ between the U.S. and EU due to different functional units.

3.3. Estimated PE demand and substitute requirements between 2020 and 2030

We estimated demand for PE packaging using market reports and published literature suitable for historical, current and short-term estimates (**Figure 1 B**). Over this decade (2020-2030), it is estimated that the overall PE demand could grow by 19% (17 to 20 MTA) in North America, by 17% (18 to 21 MTA) in Europe, and by more than 40% (117 to 155 MTA) globally (Data not shown.) For the assessed PE packaging applications, demand is expected to increase by 30% in the U.S. from 2020 levels over the same timeframe, with a compound annual growth rate (CAGR) of 2.7%. In contrast, Europe's demand is projected to rise by only 3%, with a CAGR of

0.3%. The flattening of demand in Europe may be partly due to lower expected EU GDP growth compared to the U.S. and the PPWR regulation's impact on some of the assessed PE applications (e.g., flexible packaging).

Additional BAU scenarios for the medium- to long-term (2030-2050) were also evaluated and described in Section S2. Two PE demand scenarios were assessed: a lower-demand case with modest U.S. growth and slight European decline, and a higher-demand case based on OECD projections, with stronger growth in both regions. Under both scenarios, PE packaging demand rises by 2050, and replacing PE with alternatives would greatly increase packaging mass by about 5-6 times (**Figure S5**) due to PE's higher material efficiency (Avery et al., 2025; Tacker et al., 2025).

3.4. Estimated environmental impacts of PE packaging and substitutes

We used LCI data (see previous sections and SI) and PE packaging demand to estimate the annual impacts of PE packaging (**Figure 1 B**). The weight ratios of the mix of alternative packaging material formats (paper, paper multi-material, glass, and metals) to PE from the comparative packaging LCI data were used in this analysis, assuming the alternatives can substitute PE packaging in the U.S. and the EU based on the assessed functional units. We used the annual PE demand and the substitutes-to-PE weight ratios to estimate the annual weights of required PE substitutes and their corresponding annual potential environmental impacts across six impact categories, including emissions and resource-use-related impacts.

Under the demand growth and substitution assumptions applied in this analysis, modeled impacts of the alternative materials were, in some cases, substantially higher than those estimated for PE. The assessed PE packaging in the U.S. and EU contributed 39 MTA CO_2e in 2020, increasing by 6% to 41 MTA CO_2 eq in 2024. Substituting PE packaging with alternatives could increase GWP by 190-280% in the U.S. and 50-95% in the EU (**Figure 5 A** and **G**). Projections to 2050, depending on varying demand scenarios, suggest a further increase to 46-65 MTA CO_2 eq for PE packaging in the US and EU, while also retaining the comparative GHG emission differences with alternatives (**Figure S6**). This indicates that material substitution may inadvertently exacerbate GWP impacts across regions at different levels (Meng et al., 2024).

Acidification potential (caused by acidifying emissions, e.g., SOx and NOx) over the 2020-2030 period ranged from 0.1 to 0.2 kilotons per annum (KTA) SO_2 eq in both regions.

Adopting alternatives to PE packaging could increase acidification by 280-440% in the U.S. and 240-340% in the EU (**Figure 5 B** and **H**), indicating a substantial increase in acidifying effects of material substitution on terrestrial and freshwater ecosystems. Freshwater eutrophication (related to the accumulation and build-up of eutrophying nitrogen and phosphorus emissions in freshwater ecosystems) was estimated at 1.6-2.6 KTA PO_4e between 2020 and 2030. PE substitution in the assessed applications could lead to considerable increases, exceeding 2,000% in the U.S. and 300% in the EU (**Figure 5 C** and **I**). Thus, material substitution could impose enormous burdens on aquatic systems through algal blooms driven by nutrient pollution from nitrogen and phosphorus emissions (Glibert, 2020). We note the regional disparities. The U.S. exhibits greater increases in GWP and eutrophication from PE substitution than the EU, but a smaller regional difference in acidification (**Figure 5**). These trends can be attributed to differences in packaging formats, process energy sources, and regional emission intensities.

Similarly, considerable differences in potential environmental impacts related to resource use are evident across regions. Packaging material substitution intensifies these effects. In 2024, the assessed PE applications consumed 300 PJ eq. of fossil resources in the U.S. compared to 500 PJ eq. in the EU, while alternative materials could increase fossil resource use by 30-80% in the U.S. and 10-40% in the EU. This trend continues with time as fossil resource use for the assessed PE applications is projected to increase by a 30% by 2030 from 2020 levels and almost double by 2050 to 550-660 PJ eq. in the U.S. and to 700-1100 PJ eq. in the EU, while showing a similar level of increased potential environmental impacts from PE substitution (**Figure 5 D** and **J** and Figure S6). Water-use-related environmental impacts show fewer regional contrasts than the other impacts. PE packaging resulted in water scarcity of 5-10 billion m^3 World eq. in the U.S. and water use of 8.5-13.3 billion m^3 World eq. in the EU (**Figure 5 E** and **K**). Substitutes for PE may increase these impacts by 70-120% in the U.S. and by 90-130% in the EU, respectively. Land occupation of PE application in the U.S. was estimated at 270-540 million m^2, whereas in the EU, land use was estimated at 130-200 billion points (**Figure 5 F** and **L**). PE substitution may increase land occupation or use by an order of magnitude, in the U.S. by >5000% and the EU by >1400%. Full projections for BAU to 2030 are provided in **Figure 5**, and to 2050 are provided in **Figure S6**. These findings highlight that initiatives and regulations promoting the substitution of single-use plastic can shift or increase potential environmental impacts if not guided by comprehensive, region-specific LCAs.

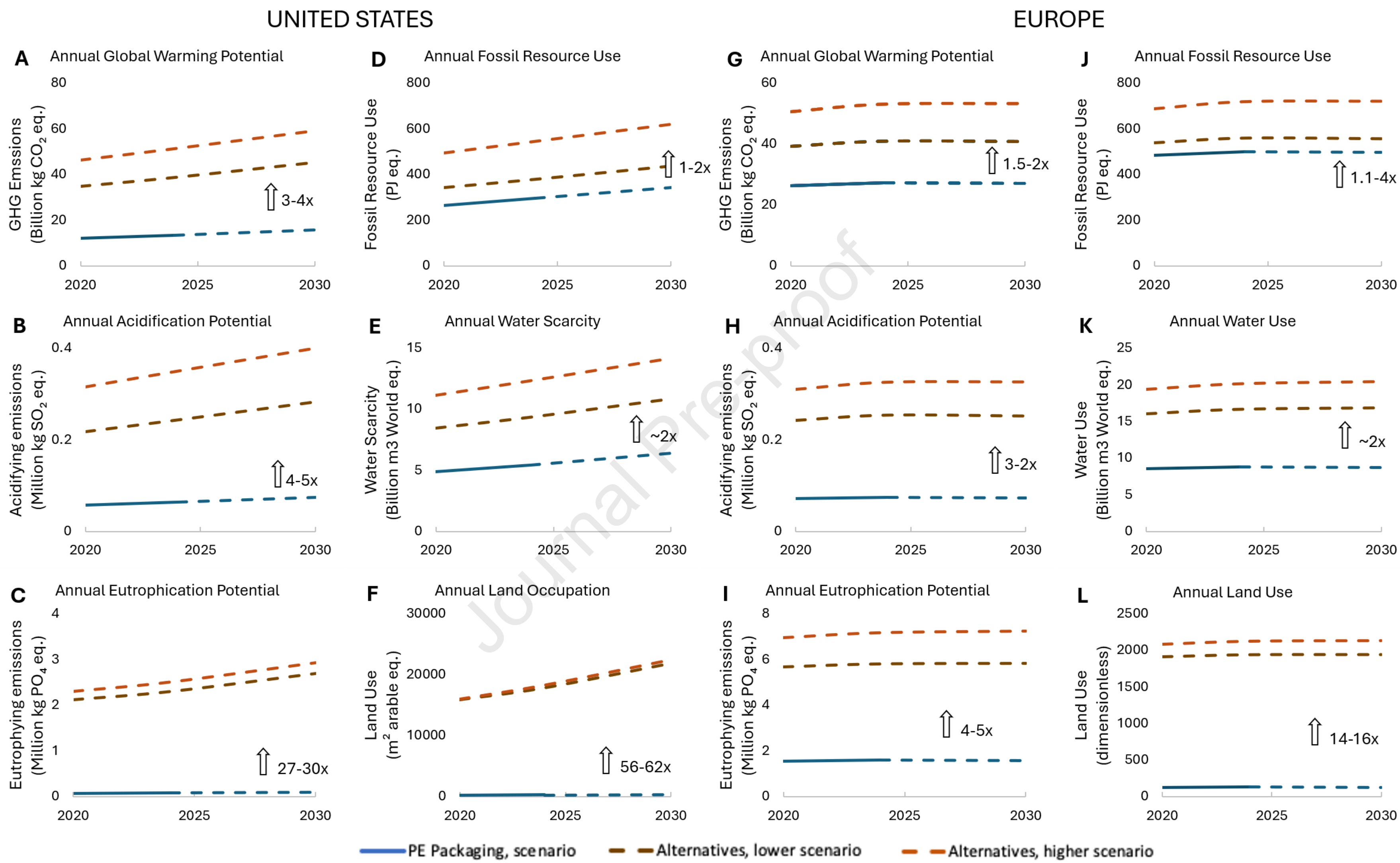

Figure 5. Potential annual environmental impacts of PE packaging and alternatives in the U.S. and Europe: A and G) GWP in billion kg CO_2 eq; B and H) Acidification in million kg SO_2eq.; C and I) Freshwater eutrophication in million kg PO_4 eq.; D and J) Fossil resource use in PJ; E and K) Water Scarcity (U.S.) and use (Europe) in billion m^3 World eq.; F and L) Land occupation (U.S.) in m^2 arable eq. and dimensionless land use (Europe). Dashed lines represent modeled or forecasted estimates.

Using in-depth LCA and PE packaging demand analyses, we demonstrated that replacing PE-based single-use packaging with alternatives such as paper, glass, or metal can result in unintended environmental consequences. With few exceptions, these material substitutions increase greenhouse gas emissions and pose greater potential environmental impacts, *including* acidification, eutrophication, and land-use, across numerous applications (see **Tables S27** to **S32**). Additionally, alternative materials typically result in heavier packaging, a consequence that can directly conflict with policies, such as the PPWR's broader objective of minimizing the overall environmental impacts of packaging (Union, 2025). The increased packaging weight may increase transportation-related emissions, resource consumption, and logistical inefficiencies.

3.5. Limitations

While the LCA presented here provides valuable insights, it is essential to recognize that such outcomes are inherently scenario dependent. Though considered trustworthy sources, the publicly available data used to develop future PE demand scenarios may not reflect historical growth rates, which were driven mostly by population and GDP growth. The current life-cycle inventories used to model future scenarios may not fully capture expected changes in electricity grid mixes, transportation emissions, manufacturing technologies, policy-driven packaging redesign, lightweighting of alternative materials, reuse infrastructure, recycled-content mandates, consumer behavior, material supply constraints, and EoL systems. Other methodologies may be better suited to project a tentative future scenario, such as prospective LCA; nonetheless, the BAU is still applicable and relevant as a general baseline. While a broad set of potential environmental impact indicators was included (10 for the U.S. and 6 for the EU), some aspects and related impacts, such as plastic littering, microplastics, chemicals from additives, environmental leakage, were excluded due to the lack of standardized LCA methodologies that can incorporate exposure conditions and pathways at local and regional scales (Cappucci et al., 2024; Harder et al., 2015), more so when considering regions where littering is still a significant challenge (Nyberg et al., 2023; Seewoo et al., 2023).

LCAs are limited in their ability to assess potential environmental impacts associated with micro and macro litter and environmental leakage of materials, including plastics, metals, paper, glass, and textiles, as well as potential impacts arising from their persistence, transformation, or degradation products in the environment and long-term ecosystem toxicity.

These impact pathways have historically been omitted or only partially represented in conventional LCI databases and consensus LCIA methods (Miller, 2022; Hajjar et al., 2024). Although recent methodological developments have begun to address some aspects of plastic pollution and microplastic formation, the scientific basis for their characterization remains insufficiently mature compared with established LCIA categories such as GWP, acidification, and eutrophication (Hajjar et al., 2023; Miller, 2022; Saling et al., 2020). Further studies could explore additional midpoint environmental footprint as they become more robust.

Key assumptions were required in areas with limited empirical data, including packaging breakage rates, transportation distances, recyclate quality, and shelf life. Product loss was outside the scope of this study; future work should evaluate the role of packaging performance in preventing product loss and waste across the supply chain. The U.S. model relied primarily on a cut-off approach for EoL modeling, potentially affecting certain downstream impact estimates for recycled materials. Although the sensitivity analysis shows consistent comparative trends between CFF and cut-off approaches, methodological choices still affect absolute impact estimates and some midpoint indicators. Therefore, results should be interpreted with the chosen allocation framework in mind, especially when comparing studies that use different EoL modeling approaches. Some of the scenario analyses, such as reuse, recycled content, and EoL, are provided for illustrative purposes; additional studies can be consulted to expand on these questions (Avery et al., 2027; Darko et al., 2023; Yudison et al., 2026; Zhang et al., 2026). Future work could also evaluate emerging recycling routes, including the upgrading of waste plastic pyrolysis oil for use as petrochemical feedstock, since such technologies may affect recycled-content availability and the environmental profile of PE packaging systems (Darko et al., 2023; Lim et al., 2025). These limitations underscore the need for improved data availability and expanded methodological frameworks in future research to ensure more comprehensive and reliable environmental assessments.

4. Conclusions

This study shows, within the framework and limitations of the analysis, that replacing PE packaging with alternative materials is not inherently a resource-saving strategy. Across five packaging uses in the U.S. and Europe, PE packaging generally had lower potential environmental impacts than paper, glass, and metal options on most midpoint indicators. The consistency of comparative results across different EoL allocation approaches (CFF and cut-off) further supports the robustness of the findings. When scaled to expected market demand, switching to alternatives would require significantly more material inputs and, in most cases, increase greenhouse gas emissions, acidification, eutrophication, water use, and land use. These findings indicate that, under the conditions modeled in this study, material substitution can shift certain environmental burdens across impact categories rather than uniformly reduce them. This study further demonstrates that methodological assumptions can influence absolute values of midpoint indicators, especially for recycling-sensitive midpoint indicators; however, the relative ranking of packaging alternatives changed minimally between methods. In particular, the comparison between the European Circular Footprint Formula and cut-off allocation illustrates the importance of considering regional methodological frameworks when interpreting LCA results. Rather than promoting a single universally applicable allocation approach, the present work highlights the need for transparent reporting of modeling assumptions and provides a framework for comparing packaging systems under the methodologies currently applied within their respective regions. The results also emphasize that packaging policies should not be based solely on material assumptions. Strategies to reduce packaging-related environmental impacts should rely on functionally equivalent, region-specific life-cycle data and consider trade-offs across impact categories, supply chains, and EoL systems. While higher recycled content, higher recycling rates, and well-designed reuse systems can lower impacts in certain situations, their effectiveness depends on logistics, infrastructure, and actual usage patterns. Future research should better incorporate factors, such as product protection, loss rates, littering, leakage, and changes in energy and waste management systems. Overall, conserving resources in packaging requires a whole-system approach rather than just switching to a different material. These results should not be interpreted as demonstrating overall environmental superiority of any packaging material, nor as predictive of outcomes under alternative design, reuse, recycling, or impact-scope assumptions not evaluated here.

Data availability statement

All data are available in the main text or the supplementary materials and references Avery et al. 2025 and Tacker et al. 2025. Further data may be requested from the corresponding authors under reasonable conditions.

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Declaration of competing interests

The authors declare the following financial interests/personal relationships, which may be considered as potential competing interests: Manfred TACKER, Elizabeth AVERY, Emma LAWRENCE, Tasja HAFNER-KUHN, and Andrin GSTÖHL report that financial support was provided by ExxonMobil Technology and Engineering Company. Manfred TACKER, Elizabeth AVERY, Emma LAWRENCE, Tasja HAFNER-KUHN, and Andrin GSTÖHL report a relationship with ExxonMobil Technology and Engineering Company that includes consulting or advisory. Rafael AURAS reports a relationship with ExxonMobil Technology and Engineering Company that includes advisory. Experience NDUAGU, Luis SOTOMAYOR, Kirti RICHA, Timothee W. ROUX are employed by Exxon Mobil Corporation or one of its affiliates.

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Manfred TACKER: Methodology, Validation, Formal Analysis, Data Curation, Writing – original draft, Writing – review & editing, Supervision. **Elizabeth AVERY**: Methodology, Validation, Formal Analysis, Investigation, Data Curation, Writing – review & editing, Supervision, Project administration. **Emma LAWRENCE**: Methodology, Validation, Investigation, Writing – review & editing. **Tasja HAFNER-KUHN**: Investigation, Resources, Writing – review & editing, Visualization, Project administration. **Andrin GSTÖHL**: Validation, Formal Analysis, Investigation. **Experience NDUAGU**: Conceptualization, Methodology, Validation, Formal Analysis, Investigation, Data Curation, Writing – original draft, Writing – review & editing, Visualization, Project Administration, Funding acquisition. **Luis SOTOMAYOR**: Conceptualization, Methodology, Validation, Data Curation, Writing – review & editing, Project Administration, Funding acquisition. **Kirti RICHA**: Conceptualization, Methodology, Validation, Data Curation, Writing – review & editing, Visualization, Funding acquisition. **Timothee W. ROUX**: Conceptualization, Methodology, Validation, Writing – review & editing, Visualization, Funding acquisition. **Rafael AURAS**:

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Highlights

- PE packaging often had lower potential environmental impacts than alternatives.
- Replacing PE with alternatives could increase packaging mass by up to fourfold.
- PE substitution may raise packaging GHG emissions 190% in the U.S. and 50% in Europe.
- Reuse, recycling, and PCR impacts depend strongly on logistics and infrastructure.
- Packaging policy should rely on functionally equivalent, region-specific LCA.

Declaration of interests

☐ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☒ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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