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Life cycle assessment of polyethylene packaging and alternatives on the European market

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ABSTRACT

Plastic packaging plays a critical role in preserving and protecting goods across value chains, including transportation, storage, marketplace, and consumption. However, growing concerns about potential environmental impacts such as life cycle emissions and plastic pollution have prompted reassessments of packaging materials. This study focuses on polyethylene (PE), the most used packaging polymer on the European market, with an annual sales volume of 4.85 million metric tons in 2023, examining its potential environmental impacts and that of alternatives such as paper, metals, and glass. The main objective of this study was to assess the potential climate change, water scarcity, and fossil resource use impacts for single-use PE packaging applications versus alternative packaging solutions within the European market. Given its comparative nature, this LCA study has followed ISO 14040:2006 and ISO 14044:2006 requirements and attributional LCA principles. Thirty-seven products packaged with PE formats and their alternatives across five end-use applications (stretch films, collation shrink films, rigid non-food containers, heavy-duty sacks, and flexible food packaging) were compared in the European markets. The assessment covered the material and production phase to end-of-life (EoL), based on current conditions in Europe (EU27 + UK). The potential impacts from the packaged product's production and usage phase were excluded. Packaging was assessed by the volume or weight of its contents, with high market share samples sourced mainly from Austria and Germany. EoL modeling followed the Circular Footprint Formula, incorporating standard disposal rates. Comparative analysis used published data on packaging and PE markets to model potential scenarios, demonstrating the life cycle GWP impacts of substituting PE-based packaging with alternatives. Results indicated that PE packaging had a lower GWP impact than steel, aluminum, and glass in 15 out of 15 comparisons. Against paper and multi-material alternatives, PE-based options were more favorable in 19 out of 35 cases, with paper alternatives being more favorable in 13 instances and three comparisons showing minimal difference – less than 10 %. PE-based packaging exhibited lower GWP in 68 %, higher GWP in 26 %, and negligible differences in 6 % of 50 LCA comparisons of PE-based packaging and alternatives. Scenario analyses suggested that substituting PE with alternatives could increase GWP from 17.5 MTA CO2-eq to between 24.5 and 28.7 MTA CO2-eq, marking a 40 %–64 % rise. The mass of packaging materials could rise from 4.85 MTA for PE to between 16.70 and 19.97 MTA (244–306 %) for alternatives, emphasizing the significant mass reduction advantage of PE-based packaging.

1. Introduction

Plastics are essential in the global economy due to their versatility, low cost, and durability. Many studies have shown the benefits of plastic packaging in protecting food and non-food products (Licciardello, 2017; White and Lockyer, 2020; Wikström et al., 2019), providing functional advantages (San et al., 2022; Yildirim et al., 2018), and reducing food loss and waste (Wikström et al., 2019). Plastics used in packaging

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applications are often lighter than comparative materials and can be tailored to specific applications and markets (Allwood et al., 2011; Cameron, 2018). These benefits have helped drive world plastic production, reaching 400 million metric tons per annum (MTA) in 2022, including 105 MTA of polyethylene production (Plastics Europe, 2023).

Demand for low-density polyethylene (LDPE), linear low-density polyethylene (LLDPE), and high-density polyethylene (HDPE) in Europe was estimated to be around 20 MTA in 2023 (Townsend Solutions, 2024). Packaging applications accounted for about 60 % of polyethylene end uses in Europe, with non-packaging applications such as agricultural films, building and construction, and consumer goods comprising the remaining demand (Townsend Solutions, 2024). Within the packaging sector, food packaging accounted for about 20 % of demand and non-food packaging for about 80 % (Townsend Solutions, 2024). Examples of non-food packaging end uses include stretch and shrink wraps, rigid bottles, bags and sacks, extrusion coatings (e.g., for lined paper), caps and closures, and others (Plastics Recycler Europe, 2020). Polyethylene can be used as a primary packaging material or be combined with other polymers or materials to form multi-material solutions that can be highly efficient for packaging applications (Bauer et al., 2021).

Recycling rates of plastics in Europe have been progressing year on year, and in 2020, the recycling rate of post-consumer plastic packaging in Europe was 46 %, with 37 % of plastics incinerated (with energy recovery) and 17 % sent to landfills (Plastics Europe, 2022). Nevertheless, there is growing concern about the adverse potential environmental impacts of plastics due to indiscriminate waste disposal, marine littering and extensive use of fossil resources, and life cycle emissions such as greenhouse gases (Di Paolo et al., 2022; Geyer et al., 2017; Helmecke et al., 2022).

There has been a growing number of LCA studies of plastic products and packaging in the last decade, often focusing on greenhouse gas (GHG) emissions measured as global warming potential (GWP) (Del Borghi et al., 2021; Di Paolo et al., 2022; Pålsson and Olsson, 2023). Plastics and polyethylene were the focus of several recent studies (Firoozi Nejad et al., 2021; Leppäkoski et al., 2023; Papo and Corona, 2022). Still, despite these efforts, no systematic research has been performed to compare the GWP and other relevant environmental impacts of a broad range of polyethylene-based packaging present on the European market with alternative materials. This is highly important considering the new European Packaging and Packaging Waste Regulation (PPWR), which includes stipulations regarding reducing the adverse impacts of packaging and packaging waste on the environment and human health (European Parliament, 2024).

A recent study assessed plastics and alternative materials in 16 end-use applications across various sectors, including packaging, focusing on the United States in 2020. The study concluded that, in most cases, plastic has a lower climate change impact than the next-best non-plastic alternative (Meng et al., 2024). While this study provides high-level estimates for general plastic applications in different regions, it did not focus on polyethylene end-use applications in Europe and relevant factors such as packaging formats, transport distances, energy mixes, and end-of-life disposal scenarios. Conclusions specific to the polyethylene packaging market may not be robust since the study focused on a broad range of plastic types and did not consider LDPE or LLDPE materials, which combined represent a large portion of PE used in the EU market.

The present study examines the potential impacts of climate change, water scarcity, and fossil resource use for polyethylene packaging (defined as containing at least 50 % PE by weight) compared to alternative packaging solutions (defined as containing less than 50 % plastic by weight) with a focus on the European market. Only single-use packaging was considered.

Thirty-seven (37) packaged products with PE-packaging formats across five end-use applications (stretch films, collation shrink films, rigid non-food containers, heavy-duty sacks, and flexible food packaging) were assessed. For each packaged product, at least one PE packaging and one alternative format were evaluated. A total of ninety-two (92) formats of PE and alternatives were compared.

2. Materials and Methods

Goal Definition: The goal of this study was to evaluate the potential environmental impacts of PE packaging versus alternative packaging solutions within the European market from cradle to end-of-life (EoL), excluding packaged product and product/package use phase (e.g., package breakage, product losses, shelf life). The study compares the potential environmental life cycle impacts of PE-based packaging with alternative materials such as paper (e.g., solid board or corrugated board), glass, aluminum, and steel. ISO 14040:2006 and ISO 14044:2006 (ISO, 2006a; ISO, 2006b) principles and requirements were followed, and an attributional LCA was conducted.

Scope Definition: Five end-use applications estimated to collectively represent about two-thirds of the PE packaging market in Europe were assessed: stretch films for pallet wraps, collation shrink films, heavy-duty sacks, rigid nonfood containers, and flexible food packaging. Within each application, one or more packaged products were considered; 37 were included in the assessment, comparing 92 unique packaging formats available on the European market across the five end-use applications, as shown in Table 1. The most relevant PE packaging formats were identified through market research. Product groups were chosen for each application where PE packaging and alternative packaging formats were present on the market (either in supermarkets in Austria and Germany or as industrial packaging). From each of these product groups, PE packaging formats with high market share and their alternatives were sampled. The sample selections highlight typical packages for each product application with high market share but are not considered representative of market averages due to the sample size. Sample compositions were then identified using packaging specifications of the weight and composition of their constituents. The functional unit of the packaging was defined by the volume or weight of the packaged product, as also shown in Table 1.

Life cycle impact assessment (LCIA) was conducted using ecoinvent 3.8 datasets (Ecoinvent Association, 2023) and openLCA (Green Delta, 2023). Three impact categories were considered in this study: climate change, water scarcity, and fossil resource use. The climate change impact category was assessed according to the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) (IPCC, 2013) using the indicator Global Warming Potential (GWP) with a time horizon of 100 years, expressed in kg CO_2-equivalent (eq.). The AR5 contained the latest GWP impact factors available in openLCA during the LCIA modeling. Water scarcity was assessed using the Available Water Remaining (AWARE) model expressed in m^3 water-equivalent (m^3 water-eq) of deprived water (Boulay et al., 2018). Fossil resource use was assessed with the approach by van Oers et al. (2002) and is characterized as MJ equivalents. The assessment was conducted to gain insight into the environmental performance and potential trade-offs that may emerge when selecting packaging materials based on the three impact categories. The assessed impact categories were considered the most significant for their relevance to climate change and resource consumption. Science and methods for determining other potential impacts, such as ecotoxicity and human health categories, were excluded from the study since they are still evolving and not yet well-established, which can generate significant uncertainties. Chen et al. (2021) reported that uncertainties can vary significantly depending on the life cycle impact assessment (LCIA) method and LCIA database used, with maximum values reported to be several orders of magnitude different than the minimum values for several impact categories (e.g., ecotoxicity and human health related impact categories) except for GWP.

The scope encompasses cradle to EoL, based on present conditions in Europe (EU27 + UK) and excludes impacts from the life cycle of the

Table 1
Description of the thirty-seven evaluated packaged products in the five PE packaging applications (collation shrink, stretch films, rigid non-food packaging, heavy-duty sacks, flexible food packaging).

Packaged Product	Functional Unit	Packaging Formats [symbol]	
		PE Packaging	Alternative(s) Packaging
Collation shrink films (14 packaging formats)			
Six 1.5 L bottles	Secondary packaging holding together six standard-sized 1.5 L PET bottles	Shrink film ([PE1], [PE2])	Corrugated carrier [P1]
Six 0.5 L bottles	Secondary packaging holding together six standard-sized 0.5 L PET bottles	Shrink film ([PE3], [PE4])	Corrugated carrier [P2]
Six 0.5 L cans	Secondary packaging holding together six standard-sized 0.5 L aluminum cans	Shrink film ([PE5], [PE6])	Paperboard box [P4], corrugated carrier [P3]
Six 0.33 L cans	Secondary packaging holding together six standard-sized 0.33 L aluminum cans	Shrink film [PE7]	Paperboard box [P7], paperboard carrier [P5] and corrugated carrier [P6]
Stretch films for pallet wraps (2 packaging formats)			
Pallet contents	Machine-wrapped standard pallet configuration [1.2 m × 0.8 m x 1.15 m; 1000 kg load]	Stretch film [PE8]	Paper wrap [P8]
Heavy-duty sacks (HDS) (12 packaging formats)			
Pre-mixed cement, 10 kg	Packaging of 10 kg pre-mixed cement	PE sack [PE9]	Paper-based sack with PE layer [M4]
Cement, 25 kg	Packaging of 25 kg standard cement	PE sack [PE10]	Paper-based sack with PE layer [M3]
Chicken fodder, 20 kg	Packaging of 20 kg chicken fodder	PE sack [PE11]	Paper-based sack with PE layer [M2]
Organic fertilizer, 10.5 kg	Packaging of 10.5 kg organic fertilizer	PE sack [PE12]	Paper sack [P10]
Fertilizer, 20 kg	Packaging of 20 kg fertilizer	PE sack [PE13]	Paper-based sack with PE layer [M1]
Wood pellets, 15 kg	Packaging of 15 kg wood pellets	PE sack [PE14]	Paper sack [P9]
Rigid non-food packaging (20 packaging formats)			
Wall paint, 10 L	Packaging of 10 L wall paint	HDPE bucket [PE15]	Tinplate steel bucket [S1]
Wall paint, 2.7 L	Packaging of 2.7 L wall paint	HDPE bucket [PE16]	Tinplate steel bucket [S2]
Dietary supplements, 140 mL	Packaging of capsules in a volume of 140 mL	HDPE bottle [PE17]	Glass bottle [G1]
Motor oil, 1 L	Packaging of 1 L motor oil	HDPE canister [PE18]	Tinplate steel canister [S3]
Household cleaner, 1 L	Packaging of 1 L household cleaner	HDPE bottle [PE19]	Paper-based bottle with PET layer [M5], glass bottle [G2]
Liquid detergent, 1.5 L	Packaging of 1.5 L liquid detergent	HDPE bottle [PE20]	Paper-based bottle with PET layer [M6]
Shampoo, 500 mL	Packaging of 500 mL shampoo	HDPE bottle [PE21]	Glass bottle [G3]
Body lotion, 250 mL	Packaging of 250 mL body lotion	HDPE bottle [PE22]	Paper-based bottle with PET layer [M7]
Body lotion, 150 mL	Packaging of 150 mL body lotion	HDPE bottle [PE23]	Glass jar [G4], aluminum can [A1]
Flexible food packaging (44 packaging formats)			
Potatoes, 1.5 kg	Packaging of 1.5 kg potatoes	LDPE bag [PE24]	Paper bag [P11]
Cashew nuts, 150 g	Packaging of 150 g whole cashew nuts	Metallized LDPE pillow pouch [PE25]	Paper-based multimaterial stand-up pouch [M20], tinplate steel can [S4]
Salt, 750 g	Packaging of 750 g salt	LDPE pillow pouch [PE26]	Paperboard box [P12], paperboard tube with plastic lid [M8]
Sugar, 1 kg	Packaging of 1 kg sugar	LDPE PET pillow pouch [PE27]	Paper bag [P13], paper-based multimaterial carton [M9]
Juice, 200 mL	Packaging of 200 mL non-carbonated juice	PET/Alu/PE stand-up pouch [PE28]	Paper-based multimaterial carton [M10], glass bottle [G5]
Produce bag, 1 kg	Ready-to-use packaging for self-filled fruits & vegetables with a carrying capacity of 1 kg	PE single use bag [PE29]	Paper single use bag [P14]
Apples, 1 kg	Packaging of 1 kg whole apples	LDPE bag [PE30]	Paperboard tray with LDPE film [M11], corrugated tray [P15]
Mayonnaise, 250 g	Packaging of 250 g mayonnaise sauce	LDPE spouted stand-up Pouch [PE31]	Glass jar [G6], aluminum tube [A2]
Hot chocolate, 350 g	Packaging of 350 g hot chocolate powder	LDPE/PET gusseted pouch [PE32]	Paperboard box [P16]], paperboard with coated paper bag [M12]
Instant coffee, 250 g	Packaging of 250 g instant coffee powder	PET/Alu/PE pouch [PE33]	Glass container [G7], tinplate steel can [S5]
Coffee, 250 g	Packaging of 250 g whole coffee beans	PET/Alu/PE gusseted pouch [PE34] & LDPE/PP gusseted pouch [PE35]	Paper-based multimaterial gusseted pouch [M13], tinplate steel can [S6]
Frozen pizza, 430 g	Deep-freeze suitable packaging of 430 g pizza	LDPE shrink film [PE36]	Laminated paper pouch [M14]
Frozen pizza bread, 300 g	Deep-freeze suitable packaging of 300 g pizza bread	LDPE/PET pillow pouch [PE37]	Laminated paperboard box [M15]
Frozen peas, 300 g	Deep-freeze suitable packaging of 300 g whole peas	LDPE pillow pouch [PE38]	Laminated paperboard box [M16]
Frozen herbs, 75 g	Deep-freeze suitable packaging of 75 g frozen herbs cut	LDPE stand-up pouch [PE39]	Laminated paperboard box [M17]
Frozen raspberries, 250 g	Deep-freeze suitable packaging of 250 g raspberries whole	LDPE pillow pouch [PE40]	Laminated paperboard box [M18]
Frozen mangos, 500 g	Deep-freeze suitable packaging of 500 g mango cubes	LDPE/PET stand-up pouch [PE41]	Laminated paperboard box [M19]

packaged product and the use phase of the packaging (e.g., breakage rates, product losses, and spoilage). Sampling was conducted in 2023 and end-of-life rates from 2018 were used for the base case, as these are the latest available rates for Europe at that time, which also include the United Kingdom (Eurostat, 2024). The packaging life cycle was divided into four phases: raw material and production, transport, distribution, and end-of-life. The raw material and production phase includes all activities from resource extraction to manufacturing the package (e.g., cradle-to-PE shrink film, cradle-to-paperboard box). The transport phase includes transporting the package or packaging materials to the package filling location. The distribution phase includes transporting packaging from the filler to the retailer or warehouse–considers only the packaging and excludes the packaged product. The end-of-life phase includes waste collection and end-of-life dispositions, including recycling, incineration, and landfilling. Packaging waste collection and recycling were modeled as curbside collection with data provided by ecoinvent. Recyclability of each packaging format was assessed, see SI (Figures S29-S48). Transport distances to incineration and sorting were 100 km each. Due to a lack of data, the following activities were considered outside the scope of this study and, therefore, excluded from the system boundary: package filling, storage at distribution centers, service at retail centers, use by the consumer or end-user, and production of the packaged product. For additional details on system boundaries specific to each packaging format assessed, see the **SI** (Figures S1-S83).

Life Cycle Inventory (LCI): Weight, dimensions, and composition of samples taken from the market were measured by Circular Analytics TK GmbH when possible. Additionally, data from packaging producers or specification sheets were used. Each packaging that was not assessed using a data sheet was analysed by physical examination. The individual components were identified based on product labelling, material properties (e.g. burn test) and estimates based on empirical values. The quantity of each material used was determined by weighing and in some cases by additional calculations. The manufacturing processes were determined through estimates based on empirical values and research. The packaging data were linked with environmental footprint estimates predominantly from ecoinvent 3.8 (cut-off, regionalized datasets) to build LCI models (SI Table S1). Care was taken to reflect geographically relevant supply chain datasets and assumptions for the European region (SI Table S2-S10) by using recommendations from the European Commission, including PEF guidance for European transport distances (SI Table S2) and the Circular Footprint Formula (CFF) for recycled content and EoL assumptions (SI Tables S9 and S10). For the calculations, 0 % post-consumer recycled content was assumed unless otherwise specified in the ecoinvent dataset. Consequently, packaging materials such as steel, chromium steel, corrugated board, and glass contain recycled content, while packaging materials such as polyethylene, aluminium, paper, and solid board do not. Including recycled content is particularly important for materials with significant differences between the primary material dataset and the recycling process, such as metals. Eurostat data were used for EoL disposition rates (SI Table S3-S5) (Eurostat, 2024).

Comparative conclusions are drawn using a 10 % margin of error, which the authors consider a reasonable threshold of significance for determining potentially higher or lower impacts based on the uncertainty of the evaluated indicators and datasets. Several sensitivity analyses were conducted, including effects of geographical location (e.g., electricity grid mix, EoL disposition rates, and transport distances), packaging weights and compositions, transport modes, and EoL assessment methodology. For further details, see SI Tables S110-S129.

3. Results and discussion

LCI data were converted to potential environmental impacts using characterization factors on an absolute basis for each of the 92 packaging formats (Table 1), comprising of 41 PE, 16 paper, 20 paper multi-material, 7 glass, 6 steel, and 2 aluminium formats, and supporting 50 unique comparisons of PE-based packaging to alternatives. The comparative results are presented here using a “substitution potential” metric, defined as the percent decrease or increase in environmental impact potentially realized using PE-based packaging relative to an alternative and calculated following equation (1).

$$\textit{Substitution potential}\ [\%] = \frac{\textit{Impact}\ [\textit{Alternative}] - \textit{Impact}\ [\textit{PE}]}{\textit{Impact}\ [\textit{Alternative}]} * 100 \qquad (1)$$

Positive values indicate that PE-based packaging had lower potential life cycle environmental impacts relative to the compared alternative. In contrast, negative values reflect higher potential life cycle environmental impacts for PE-based packaging relative to the alternative.

For each assessed impact category, when there are several PE-based formats for a packaged product, the one with the higher potential impact was selected as the basis for comparison with the PE alternatives, maintaining a conservative approach. This means that of the 41 PE formats assessed, only 37 PE packaging formats corresponding to one PE format per packaged product were used as the basis for the comparisons. For example, the PE shrink film for six 1.5 L bottles [PE1], which had a higher impact among the two PE formats, was compared with the corrugated carrier [P1]. Similarly, because of its higher impact, the PE shrink film for six 0.5 L cans [PE6] was compared with the paper-based alternatives ([P3] and [P4]).

3.1. Global warming potential

Life cycle climate change impacts, measured as GWP, for PE-based packaging and alternatives are shown in Fig. 1. The raw material and production life cycle phase has the highest relative contribution to life cycle GWP across all 92 packaging samples. This phase includes, for example, cradle-to-gate production of PE-based or alternative-based packages. End-of-life contribution to the life cycle impacts can vary significantly and, in some cases, result in a negative value due to the use of the CFF, which gives avoided burden credits for end-of-life recycling and energy recovery. Transport and distribution collectively contribute 3 %–38 % of life cycle GWP impacts, mainly correlated to the packaging weight. Metal-based packaging has relatively high recycling rates (aluminium 55 % and tinplated steel 85.5 %) and PCR contents (aluminium 0 %, steel 20 %, and for glass bottles 63–90 %). As recycling of aluminium and steel is very energy efficient compared to virgin materials, high recycling rates in Europe result in high EOL credits for metal packaging. PE collation shrink films show lower GWP than comparable paperboard wraps but higher impact than corrugated board carriers. The results are driven mostly by material efficiency, as the paperboard wraps assessed require about five times the mass of PE films, while the corrugated board carriers require only about two to three times the mass of PE films.

PE stretch films for pallet securitization show lower GWP than a paper alternative. Due to variations observed in literature data for the material required to meet the functional unit, sensitivity analysis was conducted to the mass of PE or paper wrap needed to secure pallet contents (additional information on SI section S4, Tables S27, S114). PE wraps and paper wraps would have about the same life cycle GWP at a (paper wrap to PE wrap) mass ratio of 2.8 to 1. The mass ratio of paper to PE in the base case of this study was 3.6 to 1, reflecting the market samples of PE and paper wraps collected.

Rigid non-food HDPE packaging shows lower GWP than glass, aluminum, steel, and paper-based multi-material alternatives in eight of the nine packaging comparisons. In one comparison with a paper-based multi-material bottle containing 40 % plastic by weight, the results were within the 10 % margin for error. Notably, within the rigid nonfood packaging application, the paper-based alternatives assessed are about 20–40 % plastic by weight due to the need for barrier liners and caps to ensure functional packaging performance.

Paper and paper-based multi-material heavy-duty sacks (HDS) show lower GWP than PE sacks in four of the six comparisons. The polyethylene HDS shows a lower impact in one comparison, and within the uncertainty range of 10 % in another comparison. Four of the six paper-based sacks assessed contain a PE liner for barrier protection. As the packaged product and use phase is outside the scope of this study, performance differences such as breakage rates and packaged product loss were not included. Additionally, one of the major end uses of PE HDS is to package plastic pellets; however, no paper formats could be found for this end use, so it was not represented in the study.

PE-based flexible food packaging shows 74–92 % lower life cycle GWP than the assessed glass, aluminum, and steel alternatives. The flexible PE-based packaging has a significant weight advantage, with the aluminum alternative weighing three times more, the steel alternatives weighing 11–14 times more, and the glass alternatives weighing 10–53 times more than the PE-based formats. Compared to paper and paper-based multi-material food packaging, flexible PE-based formats have lower life cycle GWP in 13 comparisons, paper and paper-based formats have lower life cycle GWP in five comparisons, and one comparison is

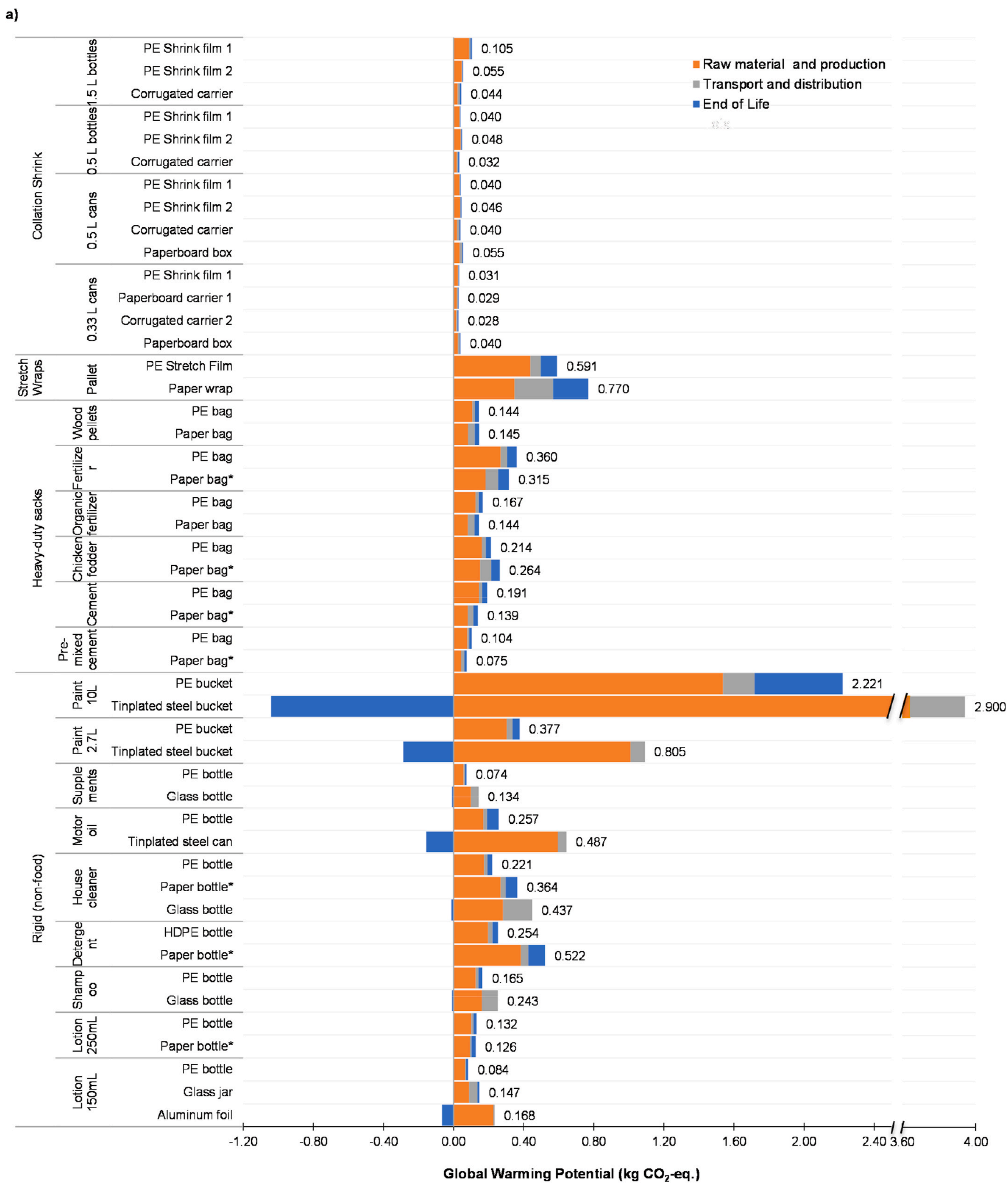

Fig. 1a. Life cycle phase breakdown for GWP impacts of PE packaging and alternatives in collation shrink, stretch wraps, heavy-duty sacks, and rigid non-food applications. Note: * represents multiple material formats.

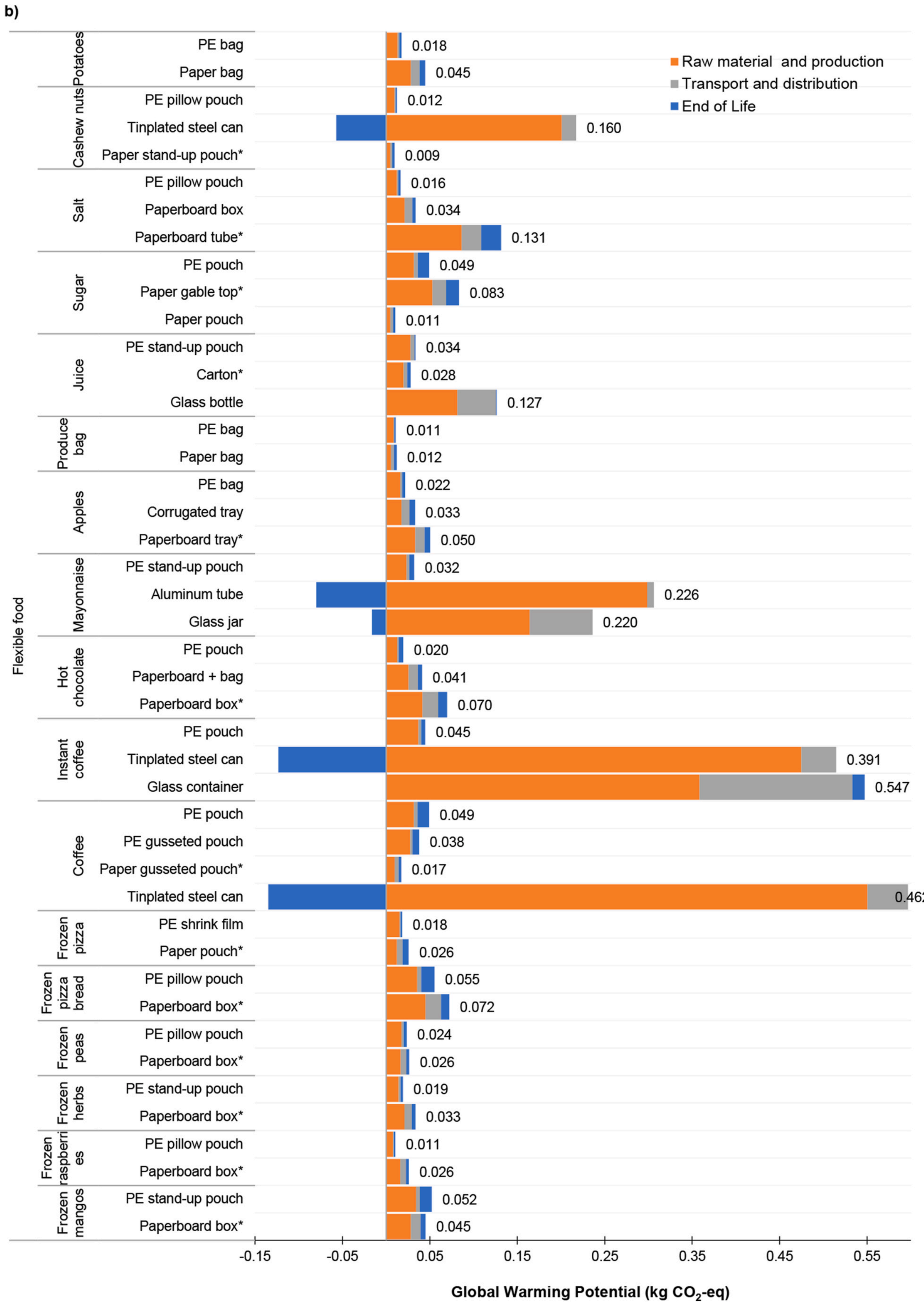

Fig. 1b. Life cycle phase breakdown for GWP impacts of PE packaging and alternatives in flexible food applications. Note: * represents multiple material formats.

within the 10 % margin of error.

Sensitivity analyses were conducted for select comparisons and provided in the SI (Section S4). They included the following parameters: package composition, recycled content, end-of-life disposition rates, CFF parameters (A-factor), electricity grid mix, transport distances, other packaging levels (i.e., primary, secondary, tertiary), and end-of-life modeling approach (cut-off, CFF) (see SI Tables S110-S129). The results are discussed in Section 4.3.

Overall, PE-based packaging has a lower climate change impact than steel, aluminum, and glass packaging across 15 comparisons with these packaging materials. Compared to paper and paper-based multi-material alternatives, PE-based packaging has a lower climate change impact in 19 of 35 comparisons, with paper-based alternatives having a lower impact in 13 comparisons, whereas three comparisons are within the 10 % margin for error. These reflect conservative GWP benefits of PE-based packaging because when more than one PE-based formats were found within a packaged product, the format with the higher impact was compared to the alternatives (e.g., paper, glass, and metals) with the

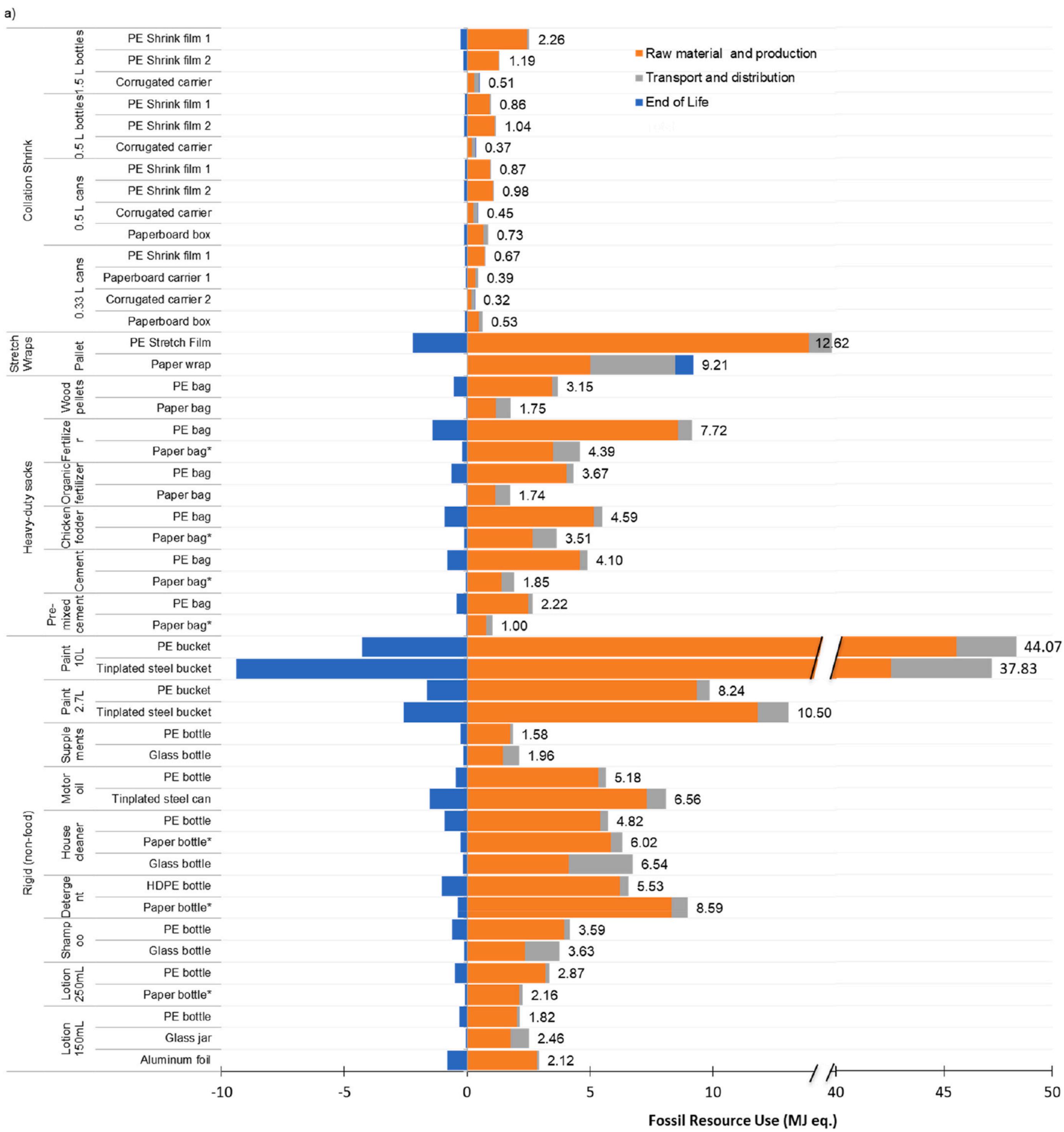

Fig. 2a. Life cycle phase breakdown of water scarcity impacts of PE packaging and alternatives in collation shrink, stretch wraps, heavy-duty sacks and rigid non-food applications. Note: * represents a package structure with multiple materials.

lower impact.

3.2. Water scarcity

The potential water scarcity impacts, in units of m^3 water-eq of deprived water, are presented in Fig. 2. This study found that using PE-based packaging has potentially lower water scarcity impact in 22 of 50 packaging comparisons. Additionally, three comparisons fall within the 10 % margin of error, and in 25 comparisons, alternative materials showed potentially lower water scarcity impacts. Analyzing material disparities, PE-based packaging demonstrates potentially lower water scarcity impact in 13 out of 15 comparisons with glass, steel, and aluminum-based formats. There is one instance where glass packaging has a lower water scarcity impact than PE-based packaging and another within the 10 % margin of error. Among the 35 mono- or multi-material paper comparisons, PE-based packaging shows lower potential impact in nine cases, with two within the 10 % margin of error. In contrast, in 24 cases, PE-based packaging shows a higher potential water scarcity impact.

PE-based non-food rigid containers show potentially lower water scarcity impact than the assessed alternative in nine of 11 (82 %) comparisons. PE-based flexible food packaging shows potentially lower water scarcity impact than the assessed alternative in 13 of 26 (50 %) comparisons. The assessed alternatives for collation shrink films, stretch wraps, and HDS showed lower water scarcity impacts in all comparisons. This variance may be attributed to different methodological approaches for paper and plastics proceeding from the ecoinvent/openLCA. For example, unpolluted water, such as cooling water, in ecoinvent datasets for various types of plastics, including PE, was treated using a Switzerland dataset while the source water came from Europe. A very low water scarcity regionalization factor for Switzerland and a high factor for Europe led to very high water inputs and low water outputs in the system, resulting in a high-water scarcity for plastics. In this study, some corrections were made to the datasets by assuming that waste water was treated in the same region it was produced. Therefore, cautionary use and interpretation of the water scarcity impact assessment results should be considered.

3.3. Fossil resource use

Fig. 3 shows the potential impacts of fossil resource use in units of MJ. The assessment indicates that PE-based packaging has the potential to reduce fossil resource use in 23 of the 50 packaging comparisons. Additionally, in three comparisons, the results fall within the 10 % margin of error, while in 24 comparisons, alternatives show lower potential impacts. Upon examining materials, PE-based packaging demonstrates potentially lower fossil resource use impacts in 12 out of 15 comparisons with glass, steel, and aluminum-based formats. One comparison with glass packaging format is within the 10 % margin of error, and in one comparison, steel packaging format exhibits a lower potential for fossil resource use than PE-based packaging. Moreover, PE-based packaging displays potentially lower fossil resource use life cycle impacts in 10 out of 35 comparisons with mono- or multi-material paper alternatives. In contrast, paper-containing materials demonstrate potentially lower fossil resource use in 23 out of the 35 comparisons. In two comparisons, PE and fiber-based packaging yield similar fossil resource use impacts based on the 10 % margin of error.

PE-based packaging shows potentially lower fossil resource use than the assessed alternatives in eight of 11 (73 %) comparisons in rigid non-food packaging applications. In the flexible packaging category, PE solutions demonstrate lower impacts in 15 of 26 (58 %) comparisons. For stretch wraps, collation shrink, and HDS, paper packaging yields lower fossil resource use than PE.

4. Discussion

Several previous studies have reported the GHG emissions associated with plastics and alternatives (Helmecke et al., 2022; Meng et al., 2023). However, they do not address the packaging formats covered in this study. So, this section explores comparative scenarios for PE-based packaging *vs.* alternatives and shows an example estimation of the potential life cycle GWP impacts of substituting PE-based packaging with alternatives in the European region and presents a sensitivity analysis of the LCA and limitations of the study.

4.1. Scenarios for comparing PE-based packaging materials and alternatives

Three scenarios were explored for comparing PE-based packaging and alternatives (paper, paper multi-materials, glass, and metals). The scenarios compare PE-based packaging with the following:

All alternatives: In this scenario, presented in the previous section, one or more comparisons are possible within a product category, depending on the number of alternative materials available. This scenario results in a total of 50 comparisons of PE-based packages and alternative material packages (paper, paper-based multi-material, glass, and metals) across the five packaging format applications, as shown in Table 1. In this scenario, Table 2 shows that PE-based packaging has potentially lower GWP than glass and metals when replacing rigid nonfood and flexible food packaging. The results fluctuate with paper and paper-based multi-materials where non-paper coatings, plastic linings, or inner plastic layers enable paper's packaging function. Conclusions reported in this study were drawn by comparing PE-based packaging to paper-based packaging regardless of whether the latter is enabled by the former (e.g., PE or plastic lining) or not.

For all the assessed packaging applications, PE-based packaging showed lower GWP in 34 of 50 (68 %) comparisons, higher GWP in 13 of 50 (26 %) comparisons, and the rest (6 % or three of 50 comparisons) are within the 10 % margin of error. The cases where PE-based materials have higher GWP are comparisons with paper (7) and paper-based multi-materials (6). PE-based packaging showed lower water scarcity in 22 of 50 (44 %) comparisons, higher water scarcity in 25 of 50 (50 %) comparisons, and the rest (three of 50 or 6 % of the comparisons) are within the 10 % margin of error. The cases where PE-based materials showed higher water scarcity are comparisons with paper (14), paper-based multi-materials (10), and glass (1). PE-based packaging has lower fossil resource use in 23 of 50 (46 %) comparisons, higher fossil resource use in 24 of 50 (48 %) comparisons, and the rest (three of 50 or 6 % of the comparisons) are within the 10 % margin of error. PE-based materials have higher fossil resource use in 13 comparisons with paper, 10 comparisons with paper-based multi-materials, and one comparison with steel-based packaging.

Highest impact alternatives: This scenario compares PE-based packaging with the alternative material with the highest potential environmental impact for a given packaged product and impact category, resulting in 37 comparisons (Table 2). In this scenario, for each impact category assessed, PE-based packaging had the highest percentage of comparisons showing a lower potential environmental impact than the alternatives. This can be attributed to PE-based packaging having potentially lower GWP than the alternatives across applications where glass and metal-based packages are the highest environmental impact alternatives. However, results fluctuate when comparing PE-based materials with paper and paper-based multi-materials (Table 2). For the assessed packaging applications, PE-based packaging showed a lower GWP in 27 of 37 (73 %) comparisons and a higher GWP in seven of 37 (19 %) comparisons, while the rest (8 % or three of 37 comparisons) are within the 10 % margin of error. The cases where PE-based materials have higher GWP are comparisons with paper (3) and paper-based multi-materials (4). For water scarcity, PE-based packaging showed a lower potential impact in 18 of 37 (49 %)

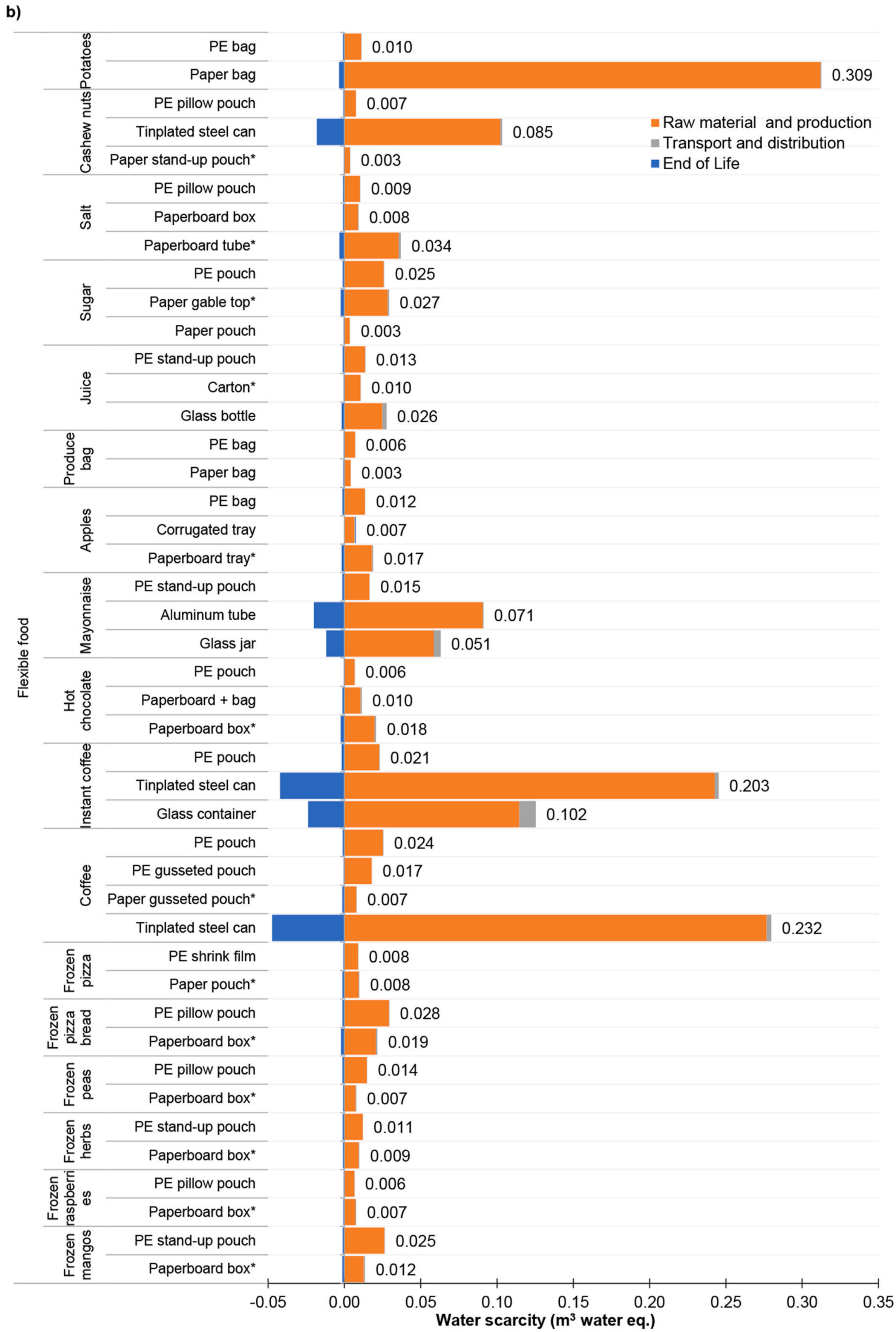

Fig. 2b. Life cycle phase breakdown of water scarcity impacts of PE packaging and alternatives in flexible food applications. Note: * represents a package structure with multiple materials.

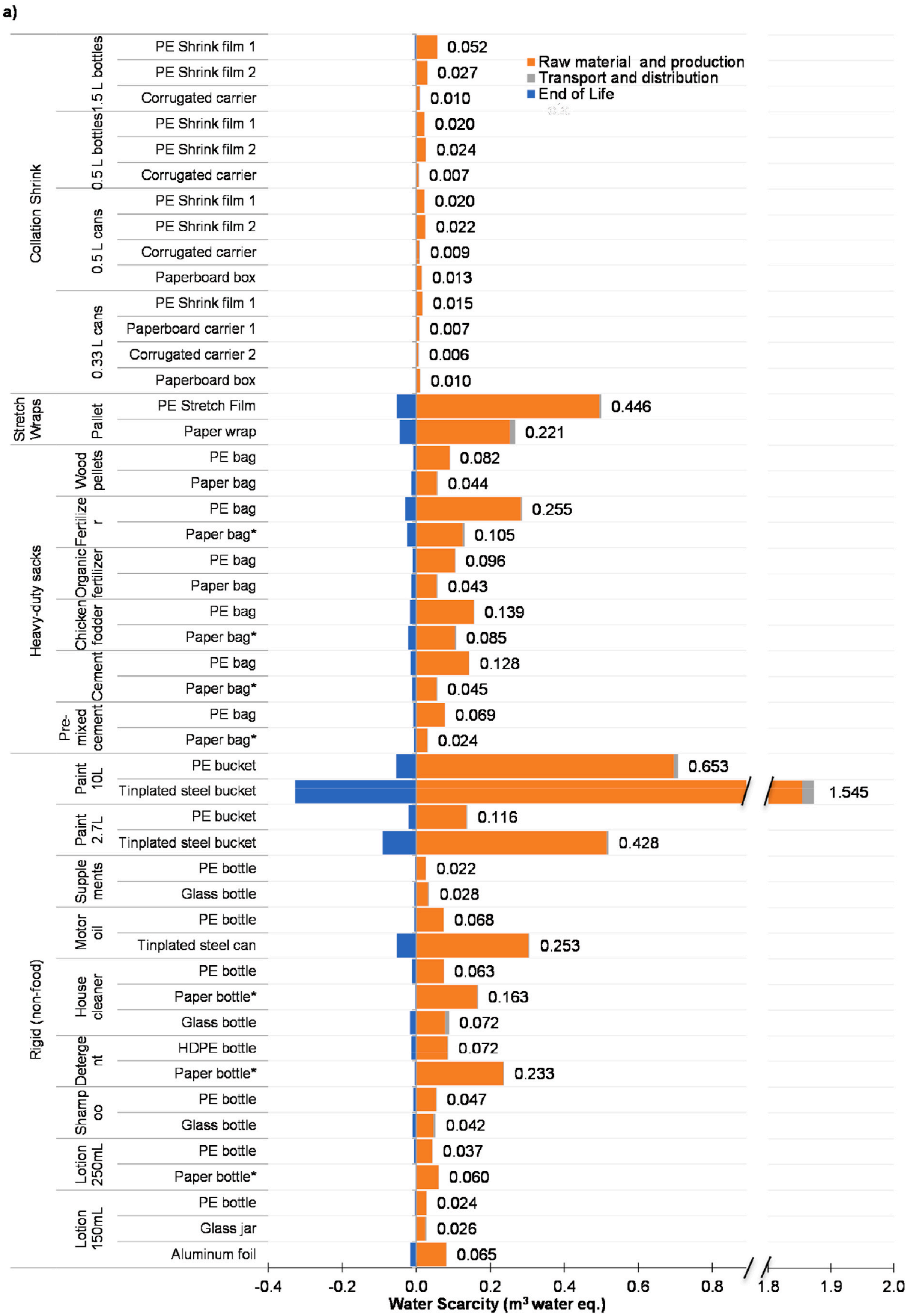

Fig. 3a. Life cycle phase breakdown of fossil resource use of PE packaging and alternatives in collation shrink, stretch wraps, heavy-duty sacks and rigid non-food applications. *Note*: * represents a package structure with multiple materials.

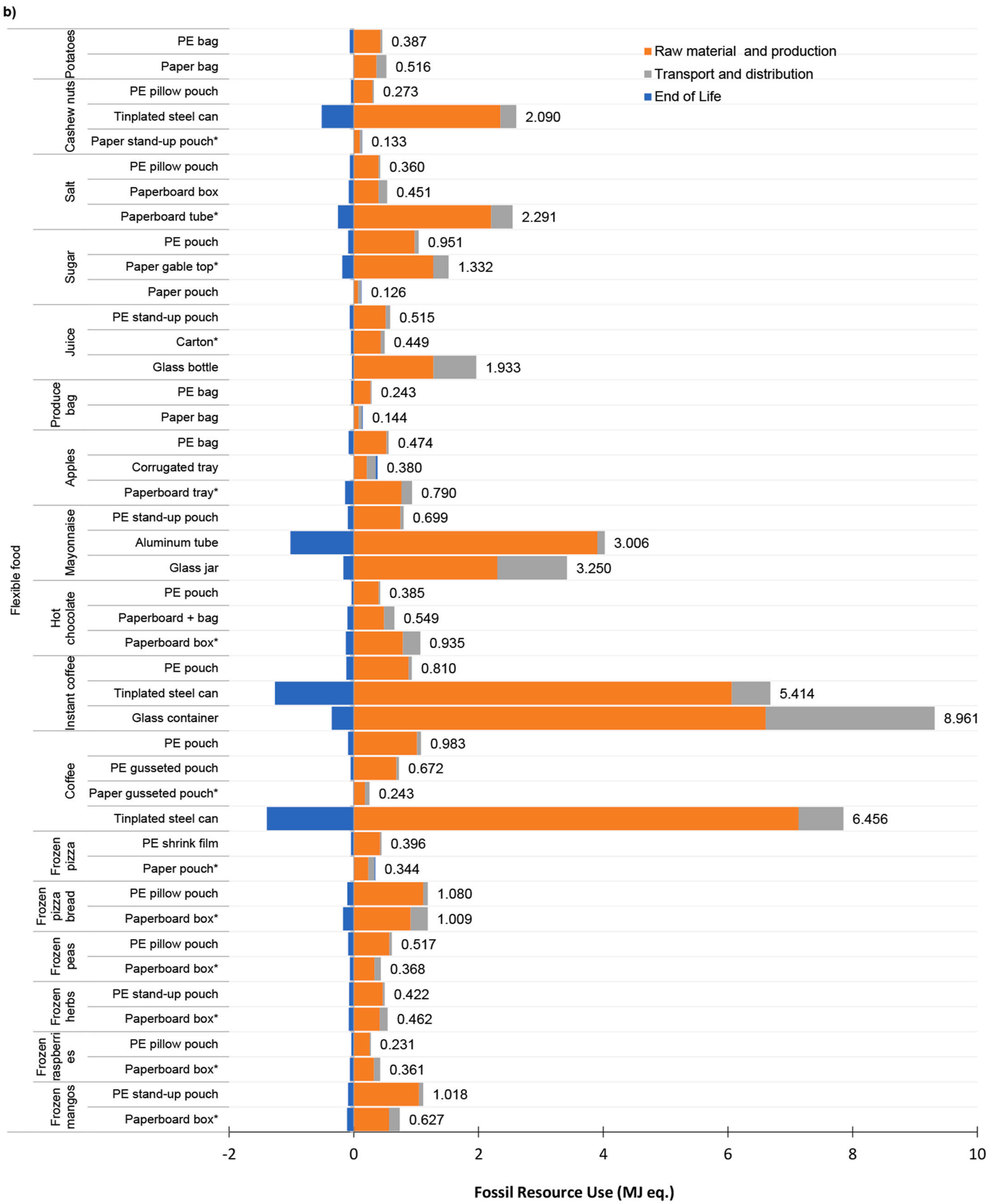

Fig. 3b. Life cycle phase breakdown of fossil resource use of PE packaging and alternatives in flexible food applications. *Note*: * represents a package structure with multiple materials.

Table 2
Scenarios for comparing LCA results of PE-based packaging and alternative materials.

Comparative Scenarios	Collation Shrink	Stretch wrap for pallet	Heavy Duty Sacks	Rigid Nonfood	Flexible food	All Applications: PE higer impact	All Applications: ±10% margin	All Applications: PE lower Impact
Global Warming Potential								
All Alternatives	P1 P2 P3 P6 P4 P7	P8	P10 M1 M3 M4 P9 M2	M7 M5 M6 S1 S2 S3 G1 G2 G3 G4 A1	M20 P13 M10 M13 M19 P15 P11 P12 P15 P16 M8 M9 M11 M12 M14 M15 M16 M17 M18 G5 G6 G7 S4 S5 S6 A2	13/50 (26%)	3/50 (6%)	34/50 (68%)
Highest Impact Alternatives	P1 P2 P4 P7	P8	P10 M1 M3 M4 P9 M2	M7 M6 S1 S2 S3 G1 G2 G3 G4	M19 P14 P11 M8 M9 M11 M12 M14 M15 M16 M17 M18 G5 G7 S4 S6 A2	7/37 (19%)	3/37 (8%)	27/37 (73%)
Lowest Impact Alternatives	P1 P2 P3 P6	P8	P10 M1 M3 M4 P9 M2	M7 M5 M6 S1 S2 S3 G1 G3 A1	M20 P13 M10 M13 M19 P14 P11 P12 P15 P16 M14 M15 M16 M17 M18 G6 S5	13/37 (35%)	3/37 (8%)	21/37 (57%)
Water Scarcity								
All Alternatives	P1 P2 P3 P4 P6 P7	P8	P9 P10 M1 M2 M3 M4	G3 G4 M7 M5 M6 S1 S2 S3 G1 G2 A1	P12 P13 P14 P15 M10 M13 M16 M15 M17 M19 M20 M9 M14 P11 P16 M8 M11 M12 M18 G5 G6 G7 S4 S5 S6 A2	25/50 (50%)	3/50 (6%)	22/50 (44%)
Highest Impact Alternatives	P1 P2 P4 P7	P8	P10 M1 M3 M4 P9 M2	G3 M5 M6 M7 S1 S2 S3 G1 A1	P14 M15 M16 M17 M19 M9 M14 P11 M8 M11 M12 M18 G5 G7 S4 S6 A2	17/37 (46%)	2/37 (5%)	18/37 (49%)
Lowest Impact Alternatives	P1 P2 P3 P6	P8	P10 M1 M3 M4 P9 M2	G3 G4 M6 M7 S1 S2 S3 G1 G2	P12 P13 P14 P15 M10 M13 M15 M16 M17 M19 M20 M14 P11 P16 M18 S5 G6	23/37 (62%)	2/37 (5%)	12/37 (32%)
Fossil Resources								
All Alternatives	P1 P2 P3 P6 P4 P7	P8	P10 M1 M3 M4 P9 M2	M7 S1 G3 M5 M6 S2 S3 G1 G2 G4 A1	P13 P14 P15 M10 M13 M14 M16 M19 M20 M15 M17 P11 P12 P16 M8 M9 M11 M12 M18 G5 G6 G7 S4 S5 S6 A2	24/50 (48%)	3/50 (6%)	23/50 (46%)
Highest Impact Alternatives	P1 P2 P4 P7	P8	P10 M1 M3 M4 P9 M2	M7 S1 G3 G2 M6 S2 S3 G1 G4	P14 M14 M16 M19 M15 M17 P11 M8 M9 M11 M12 M18 G5 G7 S4 S6 G6	17/37 (46%)	3/37 (8%)	17/37 (46%)
Lowest Impact Alternatives	P1 P2 P3 P6	P8	P10 M1 M3 M4 P9 M2	M7 S1 G3 M5 M6 S2 S3 G1 A1	P13 P14 P15 M10 M13 M14 M16 M19 M20 M15 M17 P11 P12 P16 M18 S5 A2	22/37 (59%)	3/37 (8%)	12/37 (32%)

PE Comparison Material
A Aluminum
G Glass
M Multimaterial Paper
P Paper
S Steel
PE lower Impact
PE higher impact
Within 10%

comparisons, a higher potential impact in 17 of 37 (46 %) comparisons, and the rest (5 % or two of 37 comparisons) are within the 10 % margin of error. PE-based packaging showed a higher water scarcity than paper (8), paper-based multi-materials (8), and glass (1). For fossil resource use, PE-based packaging showed a lower potential impact in 17 of 37 (46 %) comparisons, a higher potential impact in 17 of 37 (46 %) comparisons, and the rest (8 % or three of 37 comparisons) fall within ±10 % margin of error. PE-based packaging showed a higher fossil resource use than paper (8), paper-based multi-materials (8), and tin-plated steel (1).

Lowest impact alternatives: This scenario compares PE-based packaging with the alternative material with the lowest potential environmental impact for a packaged product and impact category, resulting in 37 comparisons. As expected, compared to other scenarios, this scenario has the least number of comparisons in which PE-based packaging has lower potential environmental impacts than the compared alternatives (Table 2). This is because more varied comparative results are observed with paper and paper-based multi-materials, which constitute most of the lowest impact alternatives to PE-based materials in this scenario. However, the same trend of PE-based packaging showing potentially lower GWP than glass and metals is unchanged. For all the assessed packaging applications, PE-based packaging showed lower GWP in 21 of 37 (57 %) comparisons, higher GWP in 13 of 37 (35 %) comparisons, and the rest (8 % or three of 37 comparisons) are within the 10 % margin of error. PE-based materials showed higher GWP in comparison with six paper and seven paper-based multi-materials. For both water scarcity and fossil fuel resources, PE-based packaging showed a lower potential impact in 12 of 37 (32 %) comparisons but higher water scarcity in 23 of 37 (62 %) comparisons and higher fossil resource use in 22 of 37 (59 %) comparisons. The remaining 5 % and 8 % of comparisons fall within the 10 % margin of error for water scarcity and fossil fuel resources, respectively. PE-based materials have higher water scarcity in 11 comparisons with paper and paper-based multi-materials and one comparison with tin-coated steel for motor oil. PE has a higher fossil resource use in 10 comparisons with paper, 11 comparisons with paper-based multi-materials, and one comparison with tin-coated steel.

The lowest and highest impact alternative scenarios cover various comparative results. In the lowest impact scenario, PE-based material showed a lower potential life cycle impact in the fewest comparisons with alternatives. The highest impact scenario showed the highest number of comparisons, whereas PE-based packaging showed a lower potential impact than the alternatives. Further analysis in the following sections will focus on these two scenarios.

4.2. Potential annual life cycle GWP impacts of substituting PE-based packaging with alternatives in Europe

The annual GWP impacts of substituting PE-based packaging with alternative materials were estimated for the Europe region in 2023 by combining market data on PE production and demand by end-use with the life cycle inventory data (packaging material requirements and weight substitution ratios) and the associated life cycle GWP impacts (Section 4) as shown in Equations (2)–(5):

$$\textit{Alternative weight}\ [MTA] = \textit{substitution weight ratio} * \textit{PE weight}\ [MTA] \tag{2}$$

$$\textit{Annual GWP}\ [MTA\ CO_2eq.] = \textit{Annual material weight}\ [MTA] * \textit{Life cycle GWP}\left[\frac{MTA\ CO_2eq.}{MTA}\right] \tag{3}$$

$$\textit{PE substitution GWP impact}\ [MTA\ CO_2eq.] = \textit{Annual GWP}_{[Alternative]} - \textit{Annual GWP}_{[PE]} \tag{4}$$

$$\%\,\textit{PE substitution GWP impact} = \frac{\textit{Annual GWP}_{[PE]} - \textit{Annual GWP}_{[Alternative]}}{\textit{Annual GWP}\,[PE]} * 100 \tag{5}$$

The weight of the alternative material required to substitute PE packaging is determined in Eq. (2) using a substitution weight ratio, estimated as the weight ratio of the alternative materials to PE-based packaging in accordance with the assessed functional units. The annual GWP impact of PE packaging and the equivalent for the potential PE substitute materials were determined by Eq. (3). PE substitution GWP impact (in MTA CO_2-eq. and %) was calculated in Eqs. (4) and (5), which can yield a negative or positive value, indicating a potential life cycle GWP reduction (benefit) or an increase (burden) associated with substituting PE-based packaging with alternatives, respectively.

Annual PE production and demand data are from different sources for the relevant end-use applications covered in this study: collation shrink films (AMI Consulting, 2021); stretch warps for pallet (AMI Consulting, 2021); heavy-duty sacks (AMI Consulting, 2021; AMI Consulting, 2021); rigid nonfood bottles (Ceresana, 2019; Euromonitor International, 2024; Smithers, 2018; Townsend Solutions, 2024); flexible food applications (AMI Consulting, 2021; Smithers, 2018).

Table 3 shows the estimated GWP in MTA CO_2-eq and the % benefit or burden associated with substituting PE-based packaging with the lowest and highest GWP alternatives, as presented in Table 2. Additional details of the full estimations are provided in the SI section 3, Table S109. Corrugated board, paperboards, and wraps were shown to use 1.8 to 5.0 times the mass of PE collation shrink films to wrap beverage multi-packs based on these assessed samples (Table S109 in SI). It was estimated that about 0.6–0.7 MTA of corrugated board would be needed to substitute 0.23 MTA of PE collation shrink films as secondary packaging for beverage multi-packs in Europe, corresponding to a potential decrease in life cycle GWP of 0.3–0.5 MTA CO_2-eq (Table 3). The lower GWP of the paper-based alternatives in this application was primarily due to the relatively low weight ratio of paper to PE required.

Paper pallet wraps were shown to use 3.65 times the mass of PE stretch films for pallet wraps based on the assessed samples (Table S109 in SI). Thus, 7.81 MTA paper wrap would be needed to substitute 2.14 MTA of stretch film used in this application in Europe, corresponding to a potential increase in life cycle GWP of 2.17 MTA (Table 3).

Paper-based HDS were shown to use 1.7 to 2.8 times the mass of PE heavy-duty sacks for the assessed samples (Table S109 in SI). Using market sales estimates by packaged product, 0.77–0.78 MTA paper multi-material HDS would be needed to substitute 0.32 MTA of PE HDS used for the assessed packaged products in Europe. Life cycle GWP emissions for the paper and PE sacks were within 1 % (Table 3).

Alternatives to rigid nonfood containers were shown to use 0.7 to 8.1 times the mass of PE (Table S109 in SI). Based on estimated annual European sales volumes of 1.58 MTA for the packaged products assessed in the application, alternatives would potentially increase life cycle GWP by 4.07–4.58 MTA CO_2-eq (Table 3).

Alternatives to flexible food packaging were shown to use 0.7 to 53.2 times the mass of PE-based films. Based on estimated annual European sales volumes of 0.57 MTA for the packaged products assessed in each application, alternatives would potentially increase life cycle GWP by 1.18–4.68 MTA CO_2-eq (Table 3).

Table 3
Potential annual change in life cycle GWP from substituting PE-based packaging with alternatives based on estimated PE packaging sales volumes in 2023. Positive and negative values indicate potential increases or decreases in life cycle GWP, respectively, of PE-based packaging substitution with the alternatives.

	Lowest GWP Alternatives		Highest GWP Alternatives	
Packaging Categories	MTA CO_2-eq.	%	MTA CO_2-eq.	%
Collation Shrink Film	0.46	38.0	0.31	26.0
Stretch Film for Pallet Wrap	−2.17	−30.3	−2.17	−30.3
Heavy Duty Sacks	0.00	0.1	0.00	0.1
Rigid Nonfood Bottles	−4.07	−68.8	−4.58	−77.5
Flexible Food	−1.18	−53.6	−4.68	−212.1
Total PE substitution GWP	−6.96	−39.7	−11.1	−63.4

Fig. 4a) summarizes the estimated annual PE-based packaging volumes and equivalent requirements for alternative materials based on the European market's life cycle inventories (in MTA). Substituting PE-based stretch film for pallet and collation shrink films with alternatives would potentially significantly increase the amount (weight) of packaging waste generated on the market. Those two application areas currently cause around 2.4 MTA of waste on the European market. Alternatives from paper are approximately three times heavier, and this could increase the packaging weight by more than 8 MTA. PE-based packaging in the applications studied was estimated to have an annual sales volume of 4.85 MTA on the European market in 2023 (Table S109 in SI). The mass of packaging materials put on the market would potentially increase even more substantially from 4.85 MTA for PE packaging to 16.70–19.97 MTA (244–306 %) for the alternative materials (Table S109 in SI). However, the amount of waste generated was out-of-scope of the study but could be assessed by future studies to elucidate the potential waste generation impacts of packaging materials.

Fig. 4b) shows the GWP impact as an illustrative environmental indicator, considering a similar analysis could be conducted for the other environmental indicators. The discussion of the impact of substituting PE-based packaging with alternative materials was focused on GWP as a widely accepted midpoint indicator with relatively less uncertainties (Chen et al., 2021). In the assessed scenarios, the substitution of PE with alternatives would potentially lead to an increase in GWP from 17.5 MTA CO_2-eq. to between 24.5 and 28.7 MTA CO_2-eq., which is a 40 %–63 % increase relative to the PE-based packaging in the two assessed scenarios.

4.3. *Sensitivity analyses*

Sensitivity analyses indicate that results were sensitive to geographical location effects due to differences in end-of-life dispositions, transport distances, and electric grid mixes.

EoL – Recycling Rates (RR): Higher RR significantly reduces GWP for PE, and for paper. For the pallet stretch film, increasing the RR of PE to 70 % reduces GWP by 13 %, whereas for paper, reducing the RR from 84.2 % to 50 % leads to a GWP increase of 14 % and a fossil resource use reduction of 11 % (see Tables S114 – S115 in SI).

EoL – Post-Consumer Recycled (PCR) content: Increasing the PCR content of polyethylene and aluminum significantly reduces all three impact categories assessed. For paper no sensitivity analysis was performed because there were no formats with higher PCR content detected on the market, but additional simulations of PCR increase of kraft and corrugated paper from 0 to 70 % showed only insignificant reductions of potential impacts in all three impact categories. For 150 mL bottles of body lotion, increasing PCR for HDPE bottles from 0 % to 30 % reduces the impact of climate change by only 6 %. Still, it significantly reduces fossil resource use by 10 % and water scarcity impact by 11 %. Using 50 % PCR for aluminum cans instead of the base case (PCR = 0 %) significantly reduces the climate change impact by 21 %. The effect on fossil resource use (−21 %) and water scarcity (−15 %) are also significant (see Tables S116 – S117 in SI). For glass PCR-content was already included in the ecoinvent datasets (90 % for green glass bottles).

Geographic location: The European scenario shows higher transport distances, average recycling rates, and medium landfill rates compared to GER and UK, whereas GER is characterized by higher carbon intensity of the energy mix, high recycling rates for all packaging materials, and very low landfilling rates. For the UK, the energy mix has a low-carbon intensity, and lower landfilling rates than the Europe scenario. This leads to significantly higher levels of potential impacts for transport and distribution in the European scenario, with a higher relative impact for heavier packaging materials, such as paper and steel, compared to PE. Higher carbon intensity of the GER energy mix leads to higher relative contributions of the raw material and production phase for all packaging materials. Due to a ban on landfilling of plastics and paper, the GWP of

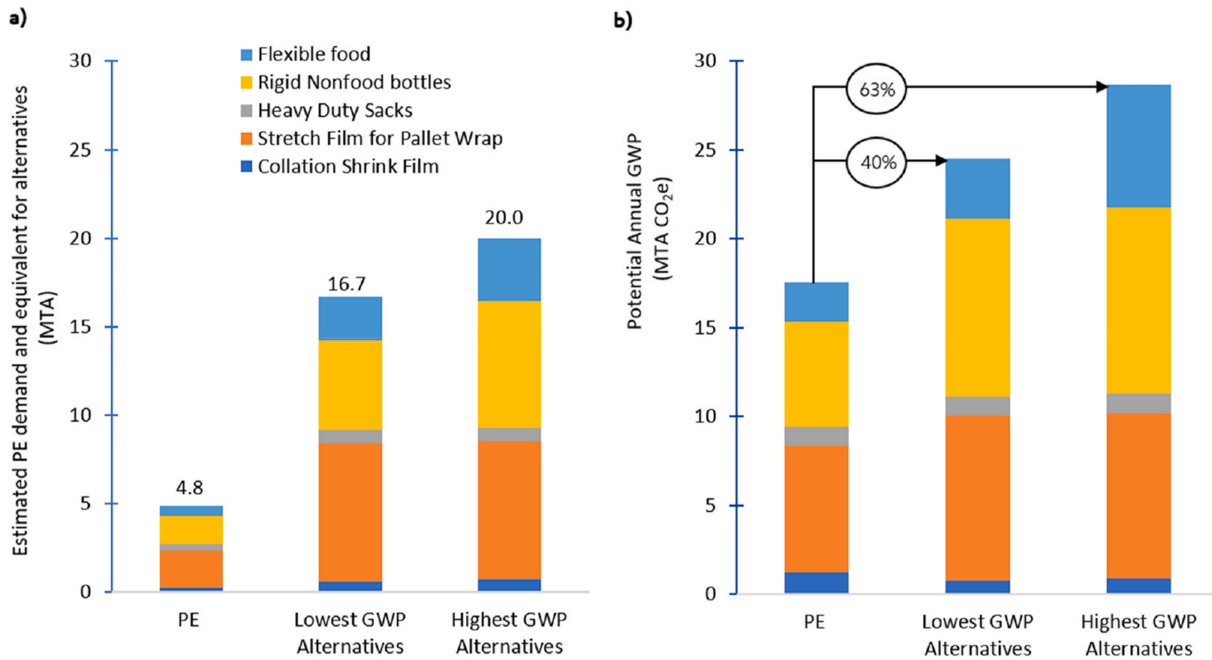

Fig. 4. a) Estimated annual PE-based packaging volumes and equivalent requirements for alternative materials based on the European market's life cycle inventories (in MTA). **b)** Potential annual GWP impact (in MTA CO_2-eq) of packaging materials and the potential % increase in GWP from PE substitution with alternatives in Europe.

paper packaging is usually lower in GER than in UK or Europe. These geographic locational considerations, in the case of PE stretch film for pallet leads to insignificant changes in the assessed impacts in GER and UK compared to Europe (see Tables S114 in **SI**). For the paper pallet wrap, significant reductions in the assessed impact categories were observed for GER and UK – the GWP is 30 % lower in GER and 21 % lower in the UK compared to the Europe scenario (see Tables S115 in **SI**).

Other parameters, such as designs of the packaging formats and weights and end-of-life methodologies (circular footprint formula *vs.* cut-off approach) also significantly, impact the results. Using the cut-off approach for the EoL assessment instead of the CFF method increases the impacts of PE-based packaging formats in the three considered environmental impact categories. For the PE stretch film for pallet, using the cut-off method increases GWP and water scarcity by ~10 % and fossil resource use by ~20 % (Table S114 in **SI**). However, for fiber-based packaging, relative to the CFF method, the cut-off approach reduces GWP and fossil resource impacts but increases water scarcity impacts. For example, for the paper wrap for pallet, using the cut-off method reduces GWP and fossil resource use by ~10 % but increases water scarcity by ~20 % (Table S115 in **SI**). This is because the CFF method evenly distributes the EoL credits and burdens from recycling and waste-to-energy recovery to the primary and secondary life cycles. But the cut-off approach attributes all the burdens from waste incineration to the first life and excludes (or cuts-off) the benefits from recycling and waste-to-energy recovery. Further details on the sensitivity analyses can be found in SI Tables S110 – S129.

4.4. Limitations of the study

Ecoinvent 3.8. database and IPCC 2013: This study uses the ecoinvent 3.8 database and IPCC 2013 available in OpenLCA at the start of and during the study period. New ecoinvent database versions and IPCC 2021 were released during and after the study concluded, as continuous updates of datasets are standard. In ecoinvent 3.9.1, the cradle-to-gate GWP for kraft paper was revised upwards by more than 33 %, and the "market for ethylene" data set changed from version 3.9.1 to 3.10 accordingly: climate change +35 %, water scarcity - 44 % and fossil resource use +6 %.

With the IPCC 2021 adapted characterization factors, recalculations of selected packaging samples showed only insignificant changes of 1–4 % compared to IPCC 2013. The same holds for ecoinvent 3.10; even if it may show substantial changes in the potential environmental impacts of PE on a per unit mass (kg) basis, only minor revisions of the directional comparisons may be expected because the effect is diluted after normalizing by the amounts of material (i.e., weight ratios of PE to alternatives) needed for the packaging formats.

Results for water scarcity should be interpreted with caution because water use inventories and regionalized scarcity characterization factors were found to be inconsistently applied in ecoinvent/openLCA for different materials (e.g. paper and plastics). For example, it was noted for several types of plastic, including PE, that "unpolluted wastewater" gets treated in Switzerland, while the source water comes from Europe. Due to a very low regionalization factor in Switzerland and a high factor in Europe, this led to very high inputs and low outputs in the system, i.e., high water scarcity. However, some corrections were made in this study by assuming that water was treated in the same region as it was used and changing the dataset accordingly. However, future studies focused on correcting the methodology discrepancy are recommended. A further limitation of the ecoinvent 3.8 is that a few datasets were available only for CH (Switzerland) and not for RER (Europe Region), so they were used as proxies for RER - this is a common practice among LCA practitioners when no data is available. This data gap constitutes a limitation because these datasets do not fully represent the European situation; however, the number of times that this data was used was minimal and fully listed in the SI Section S1.1.

Methodological limitations: In line with the goal and scope, this study focused on three key midpoint indicators–GWP, fossil resource use, and water scarcity. The study recognizes that the European PEF recommends 16 impact categories, which are beyond this study. The deliberate focus on three indicators was driven by the need to provide a robust and meaningful assessment of priority climate change and natural resource impacts. Other relatively well-developed indicators (e.g., acidification, eutrophication, ozone depletion) could provide additional environmental insights and are areas for future work; however, their inclusion would require significantly more research efforts and resources without adding more clarity to the insights. In contrast, toxicity-related indicators (human and ecotoxicity) represent a distinctly different class of impact categories, currently characterized by significant methodological uncertainties that limit their scientific reliability (Chen et al., 2021). We prioritized depth of analysis and interpretation rigor by concentrating on a few well-established midpoint indicators with robust methodological frameworks. This approach aligns with the principles of life cycle assessment, which state that meaningful interpretation is paramount to generating actionable environmental insights. Additional midpoint indicators could be addressed in future studies as methodologies and methods become more robust. The detailed impact assessment approach followed in this study found that water use inventories and regionalized scarcity characterization factors were inconsistently applied in ecoinvent/openLCA for different materials (e.g., paper and plastics). This example shows that detailed analysis is essential to ensure that results from impact categories must not be reported without scrutiny and are accurately investigated and validated. Therefore, selecting impacts to be included in LCAs should be done with an expectation of rigorous examination. The identified issues from the analysis suggest that the results for water scarcity should be interpreted with caution.

The 10 % margin of error lacks statistical underpinning but was chosen according to common practice in the LCA literature which aligns with Klöpfer and Grahl (2009), pp. 374–375, where a 10 % margin of error was applied for PET beverage bottles. For future works, it is recommended to include Monte Carlo simulations to derive impact category uncertainties and statistically significant differences.

In this study, the use phase (and thus the topic of emptiability of packaging) was excluded because emptiability is not only dependent on the packaging material but also on the type and viscosity of the product and the design of the package. The exclusion of use phase of packaging may constitute a limitation because emptiability of the packaging was not considered, and the associated product loss especially for viscous products such as body lotion or shampoo was not taken into account. This is an important topic for future research.

LCA methodology does not currently allow for reliable assessment of environmental impacts such as biodiversity loss, plastic litter and marine debris – these aspects were not included in this study.

Additional limitations:

This study concentrated on packaging present in the German and Austrian markets. To gain better insight into the European market, expansion to other countries is recommended.

Only considers single-use packaging were considered. Reusable packaging, which is especially important for materials such as glass, was not included. Due to the durable materials often chosen (e.g., glass, metals), reusable packaging typically weighs more than PE single-use packaging and often requires cleaning and maintenance cycles. Thus, it can be expected for reusable packaging formats to have higher impacts than single-use alternatives for production, transportation, and use. However, reusable packaging can be reused for multiple cycles, thus allowing the impacts to be diluted over each packaging cycle. Overall impacts are dependent on several parameters such as the number of circulations, transport distances, further handling and cleaning steps. Including reusable and refillable packaging is a potential expansion for future studies which could help identify the “break-even” points where reusable and single-use packaging alternatives have similar environmental impacts.

For EoL, the assumption for recycling was that the recyclate can be used for applications that substitute virgin material. In some cases, mechanical properties of paper and plastic recyclates can be reduced compared to virgin materials and leading to restrictions of the maximum content of recyclates in newly produced packaging or may even lead to higher weights of packaging with recycled content compared to virgin packaging to achieve the required specifications. In the CFF the quality of recyclate can be considered in the form of a quality parameter, Q_{sout}. Quality reduction of the recyclate was considered by applying the quality reduction factor Q_{sout} / Q_p of 0.75 for LDPE granulate, 0.9 for HDPE granulate, and 0.85 for paper (Table S9 in SI). For glass and aluminium, the recyclate quality is assumed not to degrade as the Q_{sout} / Q_p factor is 1.0 (Table S9 in SI). Still, additional research is necessary to determine the exact parameters for all packaging materials. Inclusion of potential quality degradation can have varying implications across material types and packaging formats. Additionally, recycling rates for packaging materials were taken from the latest available Eurostat statistics and were not differentiated between packaging types because of a lack of data. Eurostat data for recycling rates can differ since the calculation methods for recycling rates among the different countries are not yet fully aligned. Insights from sensitivity analyses indicate that in general, higher recycling rates can correlate to potentially lower life cycle environmental impacts. It should be noted that for future recycling studies of products containing biomaterials, any associated biogenic carbon uptake effect on life cycle GWP may be reduced as recycling rates increase.

Another limitation is the temporal scope. This study refers to samples collected from the market in 2023. However, the EoL rates refer to 2018. The UK is still included in the survey in that year. Therefore, the UK is part of geographical sensitivity analyses. More recent data may show improvements in recycle rates across materials at varying levels, which could lead to potentially lower life cycle environmental impacts. In future studies, other regions could be considered so that more up-to-date EoL rates can be applied. It has already been noted that the most up-to-date database should be used also in future studies to ensure that the latest data sets are used.

5. Conclusions

In its preamble, the latest Packaging and Packaging Waste Regulation highlights the need that “This Regulation should therefore establish rules covering the entire life cycle of packaging [...] preventing and reducing the adverse impacts of packaging and packaging waste”. By comprehensively evaluating GWP, water scarcity, and fossil resource use environmental impacts of PE packaging across its lifecycle from production to EoL in the European market, this study brings a timely contribution for regulators and companies making packaging choices to implement the new European Regulation. Focusing on 37 products packaged with PE-based formats and 92 unique packaging comparisons within five primary applications — stretch films, collation shrink films, rigid non-food containers, heavy-duty sacks, and flexible food packaging — the research encompassed approximately two-thirds of Europe’s PE packaging sector, making it a useful reference for most applications. The findings underscore PE-based packaging having generally lower GWP, water scarcity, and fossil resource use than heavier materials like glass, aluminum, and tin-plate steel, with PE leading in all 15 GWP comparisons. Against paper and multi-material alternatives, PE-based options demonstrated lower potential environmental impact in 19 out of 35 cases, with 13 instances where paper was more favorable and three cases showing marginal differences.

Of the 50 packaging comparisons assessed, PE-based packaging options showed lower GWP impacts in 68 % of the cases, higher impacts in 26 %, and negligible differences in 6 %. In 2023, PE-based packaging accounted for an annual sales volume of 4.85 million metric tons on the European market. Scenario analysis suggested that replacing PE with alternative packaging materials could escalate GWP emissions from 17.5 million metric tons per annum (MTA) of CO_2-eq. to 24.5 and 28.7 MTA CO_2.eq. — a 40 %–63 % increase. Furthermore, packaging materials could surge dramatically from 4.85 MTA for PE to between 16.70 and 19.97 MTA (244 %–306 %) when using alternatives, counter to the objective of the Packaging and Packaging Waste Regulation to “aim to reduce the amount of packaging placed on the market in terms of its volume and weight.” (European Parliament, 2024). These findings provide crucial insights for policymakers, elucidating the trade-offs associated with replacing packaging materials with alternatives.

CRediT authorship contribution statement

Manfred Tacker: Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Tasja Hafner-Kuhn:** Writing – original draft, Visualization, Project administration, Methodology, Investigation, Formal analysis. **Andrin Gstöhl:** Writing – original draft, Investigation, Formal analysis. **Experience Nduagu:** Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis, Conceptualization. **Eric Vozzola:** Writing – review & editing, Writing – original draft, Visualization, Investigation, Conceptualization. **Timothee W. Roux:** Writing – review & editing, Writing – original draft, Conceptualization. **Rafael Auras:** Writing – review & editing, Writing – original draft.

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: M.T.; T.H–K.; A.G., and R.A 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 following authors are employed by Exxon Mobil Corporation or one of its affiliates: E.N, E.V, and T.W.R.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cesys.2025.100270.

Data availability

Supporting Information available on www.circularanalytics.com.

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