CIRCULAR ANALYTICS

Strategies for a Transition to Circular Economy

Comparative Life Cycle Assessment of PE Packaging and Substitutes on the European Market

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Introduction

In recent years, the use of packaging materials has increased significantly, as has public awareness of environmental problems caused by incorrectly disposed waste. Packaging is, therefore, increasingly the focus of environmental policy measures. As part of the European Green Deal and the Circular Economy Action Plan, the EU is pursuing the goal of using resources more efficiently and reducing CO_2 emissions. A key instrument here is the Packaging and Packaging Waste Regulation (PPWR), which, among other things, sets ambitious recycling targets and aims to ban certain single-use packaging - such as that for fruit, vegetables or transport.

In response to these challenges and changing legislation, ExxonMobil Technology and Engineering Company commissioned a comparative Life Cycle Assessment (LCA) study from Circular Analytics to provide decision-makers with a comprehensive overview of key potential life cycle environmental impacts of different packaging materials. In a previous study, the potential environmental impacts of polyethylene-based (PE) and alternative packaging materials were assessed in the areas of Global Warming Potential (GWP), water scarcity and fossil resource use (Life cycle assessment of polyethylene packaging and alternatives on the European market). This current study also looks at polyethylene-based (PE) and alternative packaging materials with additional impact categories. The categories considered are global warming potential, acidification, eutrophication, water use, fossil resource use and land use. This comparative study was carried out in accordance with the International Standard Organization (ISO) 14040:2006 and ISO 14044:2006, the relevant standards for LCAs. The study was also critically reviewed by a panel of three independent experts.

Methodology of the Study

This study evaluates and compares GWP, acidification, eutrophication, water use, fossil resource use and land use potential impacts for 41 packaging options across 17 packaged products in five end-use applications:

- Collation shrink packaging (2 packaged products and 5 packaging formats)
- Heavy-duty sacks (2 packaged products and 4 packaging formats)
- Flexible food packaging (8 packaged products and 20 packaging formats)
- Pallet wrap (1 packaged product and 3 packaging formats)
- Rigid non-food packaging (4 packaged products and 9 packaging formats)

Packaging formats were sampled, and compositions were determined by Circular Analytics. Calculations were conducted with a Microsoft Excel tool based on the openLCA 2.1.1 software. Background and secondary datasets were mainly taken from the ecoinvent 3.10 database. Transport distances are based on the Product Environmental Footprint (PEF) guidance for the European Union, and end-of-life was modelled according to the circular footprint formula (CFF) of the European Commission Product Environmental Footprint (PEF). The EoL rates (recycling, landfill and incineration) come from various sources, including Eurostat, the European Aluminium Foil Association, Steel for Packaging Europe and a study by Cayé, Marasus & Schüler (2023).

The study focused on packaging applications made predominantly from PE with a weight content exceeding 50%, compared to alternatives such as paper, glass, steel, and aluminium, each with a content of over 50 wt.%. Some formats are considered as paper-multimaterial due to the use of plastic or other non-paper components to improve the packaging properties of the paper-based system. For the 17 PE packaged products studied, where a PE-based format was compared with one or more alternatives for a packaged product, 24 comparisons could be made (22 single-use, two multi-use). The analysis focuses on the European average market utilising packaging samples from Austria, Italy and Sweden, covering cradle-to-grave but excluding the use phase (e.g., breakage rates, product loss, shelf-life extension) in the system boundary of the LCA.

Plastics provide important performance characteristics for many packaging applications. Therefore, identifying non-plastic market alternatives was difficult for some products. In this context, it is important to note that the study only considered comparisons where the functions of packaging are similar based on functional units defined as the packaging required to contain and protect a specified quantity of product. For example, PE stretch films and collation shrink films and their paper alternatives are assumed in this study to be used to fulfil similar packaging functions under dry and indoor environments. It is important to note that the study excluded wet and outdoor environments for these applications, which are conditions where paper may not provide the similar packaging integrity of PE-based packaging. Thus, a reasonable basis for comparison was to consider only dry storage conditions for these applications.

Key Findings

Overall, PE-based single-use packaging demonstrated potentially lower GWP impacts than all studied alternatives in 17 out of 24 (71%) packaging comparisons across the five packaging applications assessed. In the acidification category, PE-based packaging showed lower potential impacts in 20 out of 24 (83%) comparisons, while in the eutrophication and land use categories, PE-based packaging exhibited lower potential impacts in 23 out of 24 (96%) comparisons. For water use, PE-based packaging had lower potential impacts in 15 out of 24 (63%) comparisons of alternative packaging formats, and for fossil resource use, PE-based packaging showed potentially lower impacts than all alternatives in 12 out of 24 (50%) comparisons across the five packaging applications assessed. In the rest of the comparisons, PE-based packaging was found to have potentially similar or higher impacts than at least one alternative in the assessed environmental impact category. Comparisons of results were made using a 10 % margin of error, which was considered a reasonable threshold of significance for determining potentially higher or lower impacts based on the uncertainty of the evaluated indicators and datasets.

The sensitivity analyses in the study reveal that various factors, such as geographical system boundary, recycling rates, post-consumer recycled (PCR) content, end-of-life allocation factors, transport distances, and energy sources, can significantly influence environmental impacts. Key findings include regional differences in impacts, with Germany and Spain showing varying results compared to the European average. Higher recycling rates and increased PCR content generally reduce environmental impacts, but effects vary by material and impact category. Shortening transport distances also leads to notable reductions in impacts, especially for heavier materials like glass. The choice of electricity source and material usage further affects the results, with renewable energy sources and reduced material use generally decreasing impacts.

GWP

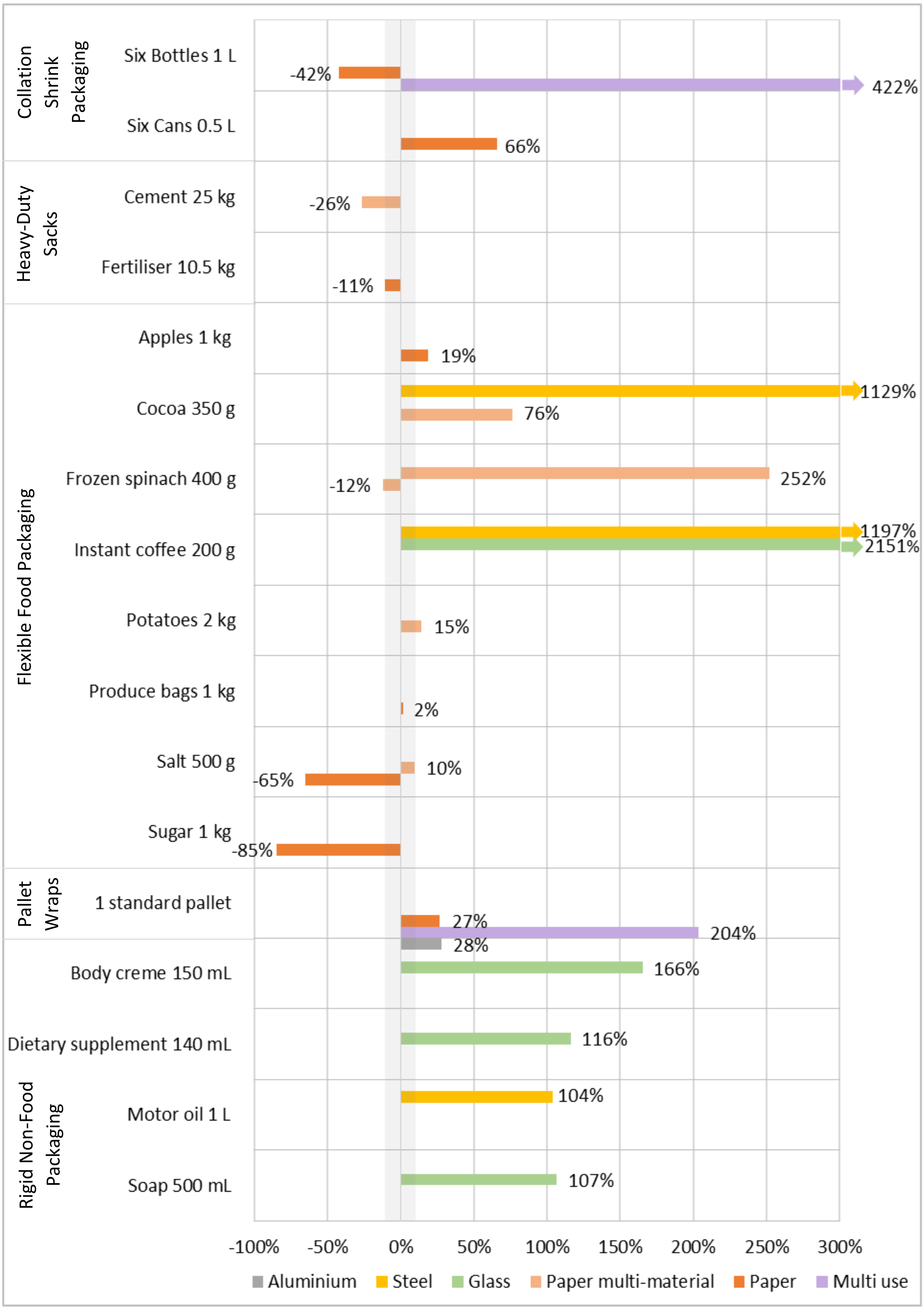

Figure 1: Substitution potential of PE - GWP| PE packaging as baseline: positive values represent higher impacts of the alternatives; negative values represent lower impacts of the alternatives. The grey area represents a 10% margin of error where the differences are insignificant. | Indicator: global warming potential (GWP100) [kg CO_2-eq]

The study found that PE-based packaging had potentially lower GWP impact than the assessed packaging alternative formats in 71% of the 24 comparisons. PE-based packaging was found to have a lower GWP impact than at least one alternative in 4 out of 5 packaging applications studied. In collation shrink packaging, alternatives to PE-based packaging formats have a higher GWP impact than PE-based formats in 50% (1/2) of the comparisons. Using a corrugated board carrier instead of PE shrink film could reduce impacts by 42% while replacing it with solid board wrap increases the impact by 66%. Using multi-use packaging, however, could lead to a significant increase of 422% in GWP impacts compared to single-use PE. In heavy-duty sacks, PE formats have a higher GWP impact than the alternatives (paper-multimaterial sack for cement and paper sack for fertilizer), which can reduce the potential impact by 11-26%. In flexible food packaging, PE formats have a lower impact in 50% (4/8) of the comparisons. Depending on the alternative, the GWP impact can either be reduced by up to 85% (paper bag) or increased by over 2151% (glass jar). For pallet wraps, switching from PE to paper wrap increases GWP impacts by 27%, and multi-use packaging leads to a 204% higher impact. In rigid non-food packaging, alternatives to PE consistently show a higher impact than PE, with increases ranging from 28% (aluminium can) to 166% (glass jar). Overall, while PE-based packaging generally has lower GWP impacts, the effect varies significantly depending on the packaging format and material used.

Acidification

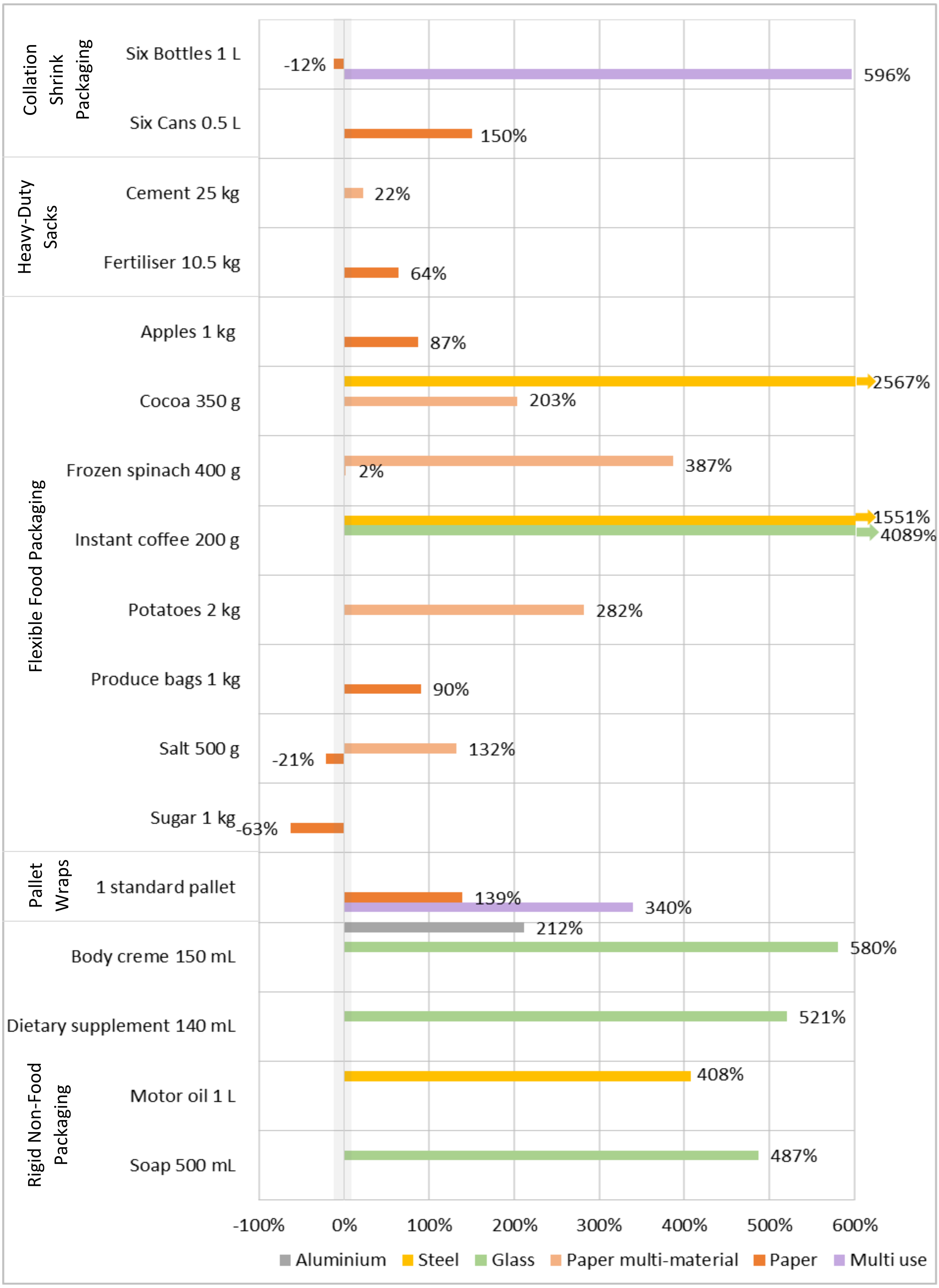

Figure 2: Substitution potential of PE - Acidification| PE packaging as baseline: positive values represent higher impacts of the alternatives; negative values represent lower impacts of the alternative. The grey area represents a 10% margin of error where the differences are insignificant. Indicator: Accumulated Exceedance (AE) [mol H+ eq]

The study found that PE-based packaging had the potential to lower the acidification impact among assessed packaging alternatives in 83% of the 24 comparisons. PE-based packaging was found to have a lower acidification impact than at least one alternative in all 5 packaging applications studied. In collation shrink packaging, PE-based packaging formats had a lower acidification impact than PE-based formats in 50% (1/2) of the comparisons. Using a paper wrap with a corrugated board carrier instead of PE packaging could reduce the acidification impact by 12% while using a solid board wrap instead of PE packaging would increase the acidification impact by 150%. Multi-use packaging, however, can lead to a significant increase of 596% in acidification impacts compared to single-use PE. In heavy-duty sacks, PE formats had a lower acidification impact in 100% (2/2) of the comparisons. Using paper and paper-multimaterial sacks instead of PE would increase the acidification impact by 22-64%. In flexible food packaging, alternatives to PE formats had a higher acidification impact in 75% (6/8) of the comparisons. Compared to flexible PE-based packaging the use of alternatives could either reduce acidification impact by 21% (paper bag for salt) to 63% (paper bag for sugar) or increase it by 87% (corrugated board tray for apples) to 4089% (glass jar for coffee). For pallet wraps, switching from PE to paper wrap would increase the acidification impact by 139%, and to multi-use packaging could lead to a 340% higher acidification impact. In rigid non-food packaging, non-PE alternatives consistently showed higher acidification impacts than PE, with increases ranging from 212% (aluminium can for body creme) to 580% (glass jar for body creme). Overall, while PE-based packaging generally has lower acidification impacts, the effect varies significantly depending on the packaging format and material used.

Eutrophication, Freshwater

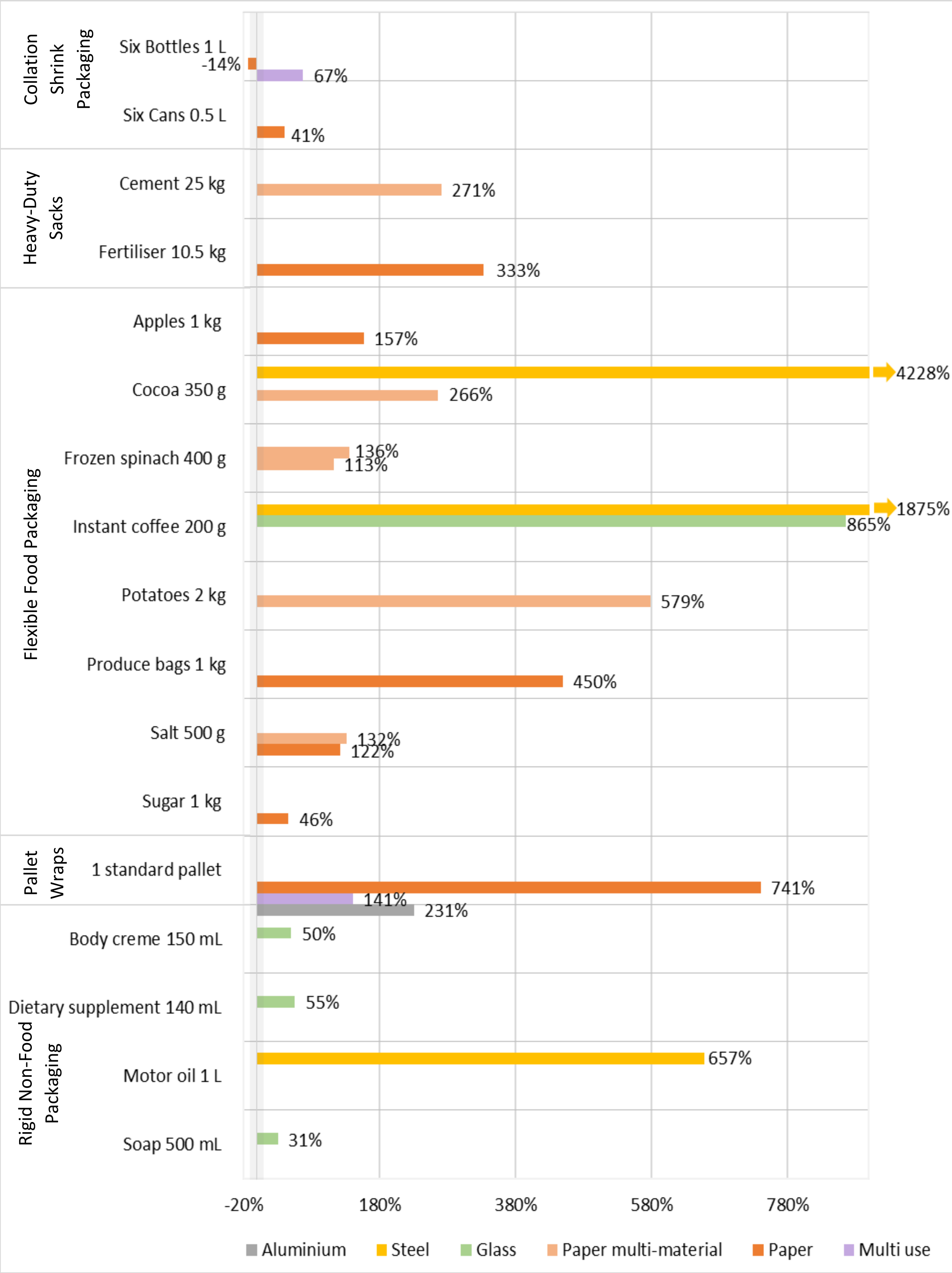

Figure 3: Substitution potential of PE - Eutrophication| PE packaging as baseline: positive values represent higher impacts of the alternatives; negative values represent lower impacts of the alternative. The grey area represents a 10% margin of error where the differences are insignificant. Indicator: Fraction of nutrients reaching freshwater end compartment (P) [kg P eq]

The study found that PE-based packaging had the potential to lower eutrophication impact among assessed packaging alternatives in 96% of the 24 comparisons. PE-based packaging was found to have lower eutrophication impact than at least one alternative in all 5 packaging applications studied. In collation shrink packaging, alternatives to PE-based packaging formats had a higher eutrophication impact than PE-based formats in 50% (1/2) of the comparisons. Using a paper wrap with a corrugated board carrier instead of PE packaging could reduce the eutrophication impact by 14% while using a solid board wrap instead of PE packaging would increase the eutrophication impact by 41%. Multi-use packaging, however, leads to a significant increase of 67% in eutrophication impacts compared to single-use PE. In the heavy-duty sacks application, formats with materials alternative to PE had a higher eutrophication impact in 100% (2/2) of the comparisons. Using paper sacks instead of PE would increase the eutrophication impact by 271-333%. For flexible food packaging, non-PE formats had a higher eutrophication impact in 100% (8/8) of the comparisons. Depending on the alternative, the eutrophication impact could be increased by 46% (paper bag for sugar) to 4228% (steel can for cocoa). In the pallet wraps application, switching from PE to paper wrap would increase the eutrophication impact by 741%, and multi-use packaging leads to a 141% higher eutrophication impact. For rigid non-food packaging, non-PE alternatives consistently showed higher eutrophication impacts than PE, with increases ranging from 31% (glass bottle for soap) to 657% (steel canister for motor oil). Overall, while PE-based packaging generally has lower eutrophication impacts, the effect varies significantly depending on the packaging format and material used.

Water Use

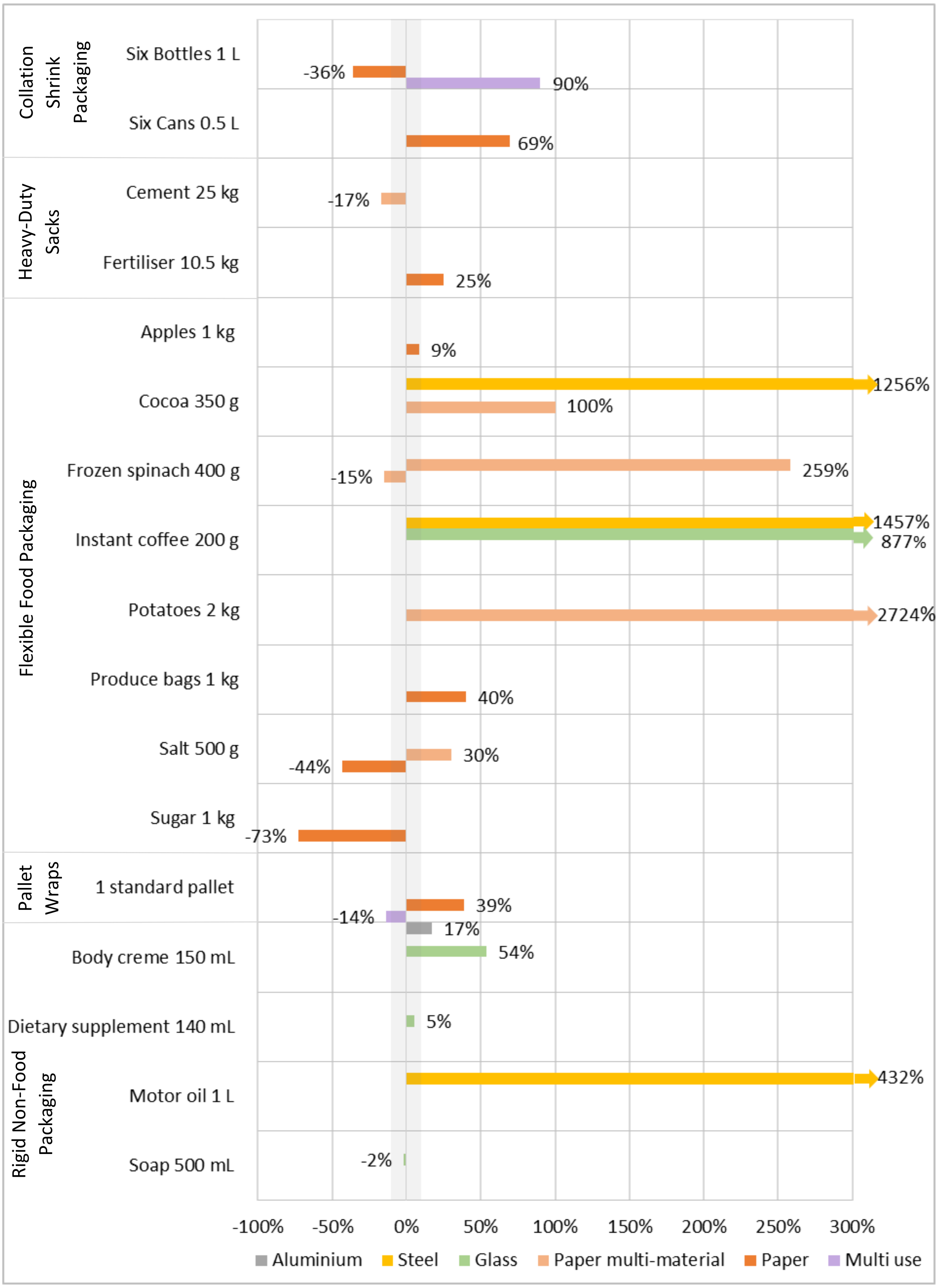

Figure 4: Substitution potential of PE – Water use| PE packaging as baseline: positive values represent higher impacts of the alternatives; negative values represent lower impacts of the alternative. The grey area represents a 10% margin of error where the differences are insignificant. Indicator: User deprivation potential (deprivation-weighted water consumption) [m3 water eq water deprived]

The study found that PE-based packaging had the potential to lower water use impacts among assessed packaging alternatives in 63% of the 24 comparisons. PE-based packaging was found to have lower water use impacts than at least one alternative in all 5 packaging applications studied. In the collation shrink packaging application, non-PE-based packaging formats had a higher water use impact than PE-based formats in 50% (1/2) of the comparisons. Using a paper wrap with a corrugated board carrier instead of PE packaging could reduce the water use impact by 36% while using a solid board wrap instead of PE packaging would increase the water use impact by 69%. The use of multi-use packaging can lead to an increase of 90% in water use impacts compared to single-use PE. For heavy-duty sacks, non-PE formats had a higher water use impact in 50% (1/2) of the comparisons. Using paper sacks instead of PE would increase the water use impact by 25%, while using a multi-material paper sack could reduce the impact by 17%. In the flexible food packaging application, non-PE formats showed a higher water use impact in 63% (5/8) of the comparisons. Depending on the alternative, the water use impact could either be increased by 30% (multi-material solid board box for salt) to 2724% (multi-material paper bag for potatoes) or reduced by 15% (multi-material paper pouch for frozen spinach) to 73% (paper bag for sugar). In the pallet wraps application, switching from PE to paper wrap would increase the water use impact by 39%, and multi-use packaging leads to a 14% reduction in water use impacts. In rigid non-food packaging, non-PE alternatives had a higher water use impact than PE in 50% (2/4) of the comparisons. Using alternative packaging instead of PE packaging would increase the water use impact by 17% (aluminium can) to 432% (steel canister). In the other 50%, the difference is not in the margin of error. Overall, while PE-based packaging generally has lower water use impacts, the effect varies significantly depending on the packaging format and material used.These results are more robust because the current study corrected discrepancies in water use datasets and regional factors that were identified in the previous study (Life cycle assessment of polyethylene packaging and alternatives on the European market).

Fossil Resource Use

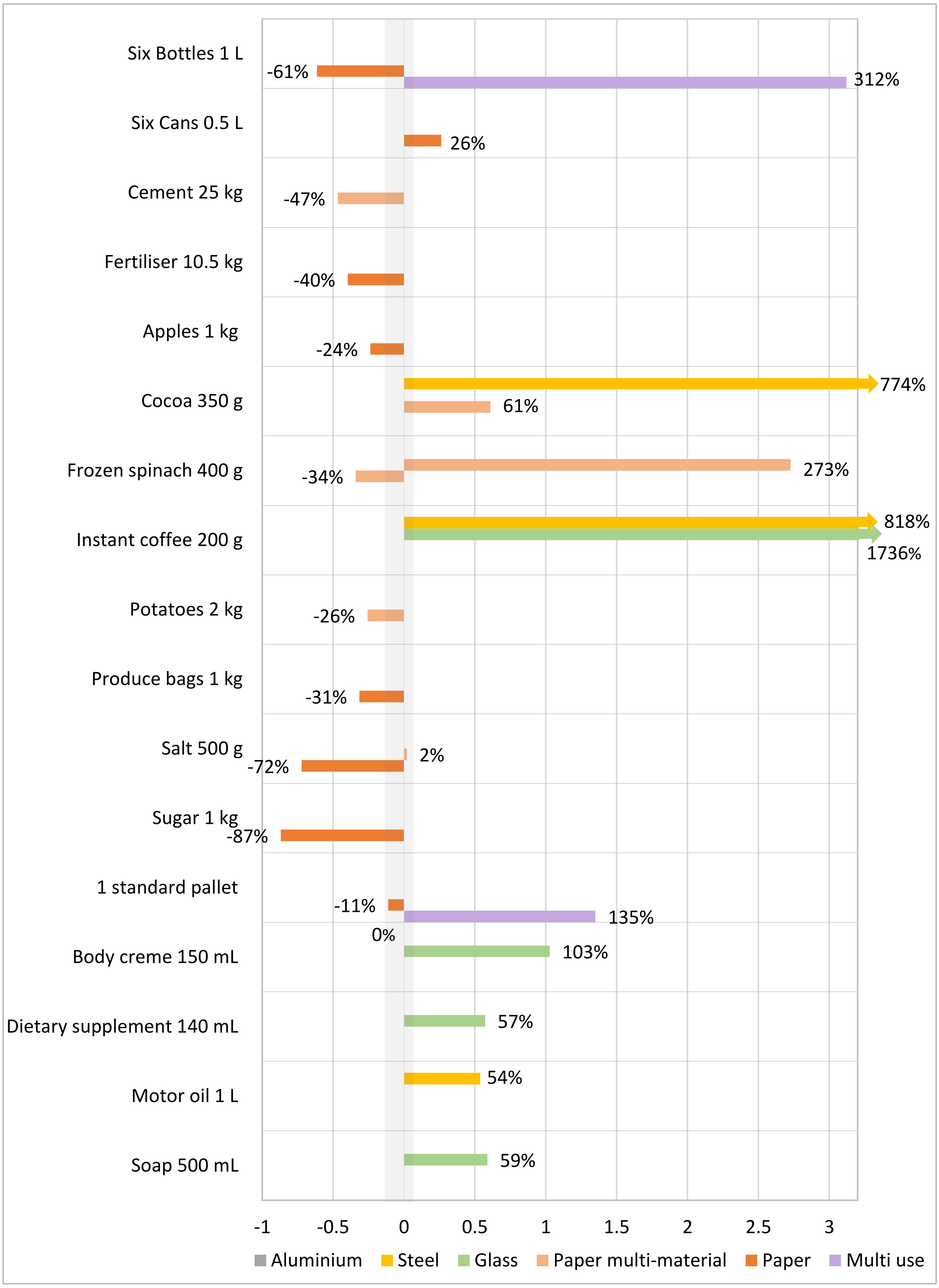

Figure 5: Substitution potential of PE – Fossil resource use | PE packaging as baseline: positive values represent higher impacts of the alternatives; negative values represent lower impacts of the alternative. The grey area represents a 10% margin of error where the differences are insignificant. Indicator: Abiotic resource depletion – fossil fuels (ADP-fossil) [MJ]

PE-based packaging showed potentially lower fossil resource use impacts among assessed packaging alternatives in 50% of the 24 comparisons. PE-based packaging was found to have lower fossil resource use than at least one alternative in 4 out of 5 packaging applications studied. In the collation shrink packaging application, alternatives to PE-based packaging formats had a higher fossil resource use impact than PE-based formats in 50% (1/2) of the comparisons. Using solid board wrap instead of PE packaging would increase the fossil resource use impact by 26% while replacing PE packaging with a combination of a paper wrap and a corrugated board carrier could lower the impact by 61%. On the other hand, using multi-use packagingcould result in a 312% higher fossil resource use impact compared to single-use PE. For heavy-duty sacks, non-PE formats had a higher fossil resource use impact than PE in 0% of the comparisons. Using paper sacks instead of PE packaging would lower the fossil resource use impact by 40% to 47%. In flexible food packaging application, alternatives to PE formats had a higher fossil resource use impact than PE in 25% (2/8) of the comparisons. Depending on the alternative, the impact could either increase by 61% (multi-material solid board box for cocoa) to 1736% (glass jar for instant coffee) or decrease by 24% (corrugated board tray for apples) to 87% (paper bag for sugar). In pallet wraps, switching from PE to paper wrap would lower the fossil resource use impact by 11%, while multi-use packaging could increase fossil resource use by 135% compared to single-use PE. In the rigid non-food packaging application, alternatives to PE had a higher fossil resource use impact than PE formats in 100% (4/4) of the comparisons. Using alternative packaging instead of PE packaging would increase the fossil resource use impact by 54% (steel canister for motor oil) to 103% (glass jar for body creme). Though with higher embodied fossil energy content, which is included in the fossil resource use, than the alternatives, PE-based packaging has lower fossil resource use impacts than alternatives in some cases, the effect varying significantly depending on the packaging format and material used.

Land Use

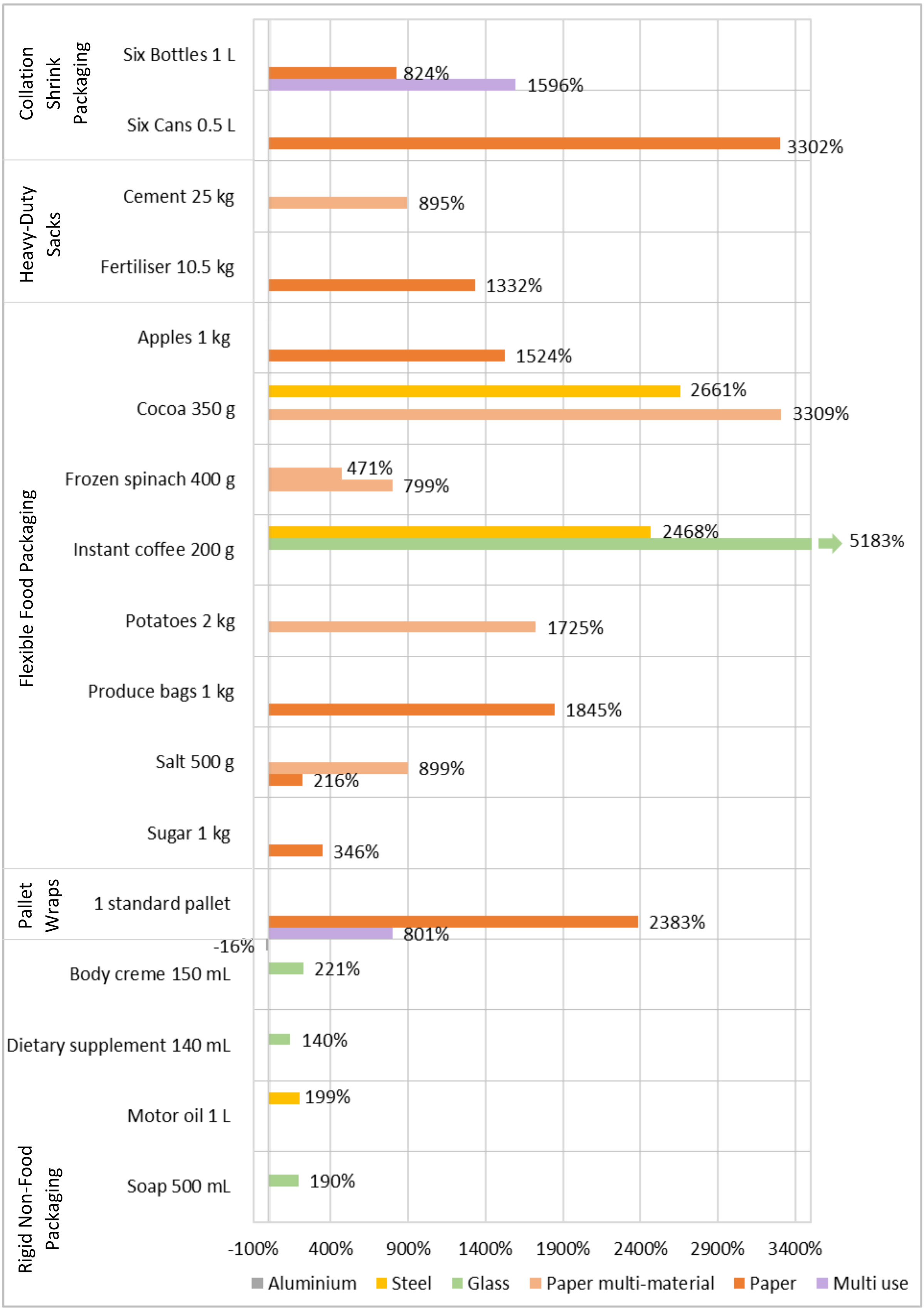

Figure 6: Substitution potential of PE – Land use | PE packaging as baseline: positive values represent higher impacts of the alternatives; negative values represent lower impacts of the alternative. The grey area represents a 10% margin of error where the differences are insignificant. Indicator: Soil quality index [Dimensionless (pt)]

The study found that PE-based packaging had the potential to lower land use impacts among assessed packaging alternatives in 96% of the 24 comparisons. PE-based packaging was found to have lower land use impacts than at least one alternative in all five packaging applications studied. In collation shrink packaging, alternatives to PE-based packaging formats had a higher land use impact than PE-based formats in 100% (2/2) of the comparisons. Using paper wrap with a corrugated board carrier instead of PE packaging would increase the impact on land use by 824% while replacing it with solid board wrap would lead to a 3302% increase. The use of multi-use packaging would result in a 1596% higher land use impact compared to single-use PE. In heavy-duty sacks, non-PE formats had a higher land use impact than PE in 100% (2/2) of the comparisons. Using paper sacks instead of PE would increase the land use impact by 895% to 1332%. In flexible food packaging, non-PE formats had a higher land use impact than PE in 100% (8/8) of the comparisons. Using alternative packaging instead of PE packaging would increase the land use impact by 216% to 5183%. In pallet wraps, switching from PE to paper wrap would increase the land use impact by 2383%, while multi-use packaging could potentially lead to 801% less land use impact compared to single-use PE. In rigid non-food packaging, alternatives to PE packaging had a higher land use impact than PE in 75% (3/4) of the comparisons. Using alternative packaging instead of PE packaging would increase the land use impact by 140% to 221% (glass jar for dietary supplement and steel can for body crème), but using an aluminium can for body crème instead of PE packaging could reduce the land use impact by 16%. Overall, PE-based packaging generally has lower land use impacts, but this effect varies significantly depending on the packaging format and material used.

Conclusion

This study aims to provide valuable insights that can support stakeholders and decision-makers in making informed, science-based decisions regarding the potential environmental impacts of PE-based packaging compared to alternative packaging materials, such as paper, glass, steel, and aluminium. The study draws the following conclusions:

- PE-based packaging has a lower potential environmental impact than alternatives made of paper, glass or metal in the majority of cases. PE often performs better than alternatives, particularly in the categories GWP (71% of comparisons), acidification (83%), eutrophication (96%), land use (96%) and water consumption (63%). PE also performs better in terms of fossil resource consumption in 50% of the cases.
- Exceptions: Paper sacks for heavy packaging consume fewer fossil resources than PE. Multi-use packaging for pallets sometimes performs better in terms of water consumption and land use but has a significantly higher impact for GWP, acidification and eutrophication. In rigid non-food packaging, aluminium can have a lower land use, while paper packaging also shows advantages in some applications in terms of water or resource use. However, other alternatives such as glass and steel lead to significantly higher environmental impacts in many cases, sometimes with an increase of more than 1000% for certain impacts.
- Plastics and other materials can enable paper to fulfil packaging functions which may not be met by paper alone. For example, six out of 14 of the paper-based packaging examples studied were multi-material formulations with plastic layers or components to provide the required performance attributes.
- In this study, multi-use systems (crate for bottles and pallet wrap) always had higher impacts than the single-use PE packaging, except in the water use category where the pallet wrap had lower impact.
- Sensitivity analysis showed that the geographical system boundary, the recycling rate, the post-consumer recycled content, the end-of-life allocation factor, the transportation, the recycling of fibre-based materials, renewable and nuclear electricity, the amount of material for pallet wraps, the presence of a sleeve or multi-use systems influence the results. If renewable energy is used in the production of packaging materials, then the environmental impact, particularly for energy-intensive materials such as aluminium, steel, and plastics, can be significantly reduced. If packaging weight is reduced without impairing its functionality of protecting the product, impacts across the whole life cycle would decrease, as less material is needed. The use of PCR reduces the need for new materials and lowers the energy intensity of the production of the raw material.
- Increasing recycled material content and recyclability of PE-based packaging and metal and glass alternative formats show a general trend of reductions in the considered potential environmental impact categories for packaging materials.
- The study found no distinct trend in which material has the lowest overall potential environmental impacts considering the six impact categories assessed. Factors such as packaging material composition and packaging format designs and weights were found to be important parameters in the analyses.

Note that use-phase packaging performance differences, such as product shelf-life, breakage rates, and product losses, are excluded from the study and may affect the results. Future studies can address these aspects to better account for performance characteristics of packaging materials and their ability to deliver packaging functions.

Any scenarios discussed herein reflect the modeling assumptions and outputs of the authors. Any reference to ExxonMobil Technology and Engineering (ExxonMobil) support of or collaboration with a third-party organization does not constitute or imply an endorsement by ExxonMobil or its affiliates of any or all of the positions or activities of such organization. When reviewing any such information, considerable uncertainty exists as to the modeling assumptions and outputs used as well as applicable government policies, technology, geopolitics, economics, and consumer preferences.