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RESEARCH ARTICLE

Life Cycle Assessment of Virgin and Recycled Polypropylene Kitchenware in the UK: Impacts of Domestic Recycling, International Supply Chains, and Consumer Use

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Abstract

This study evaluates the cradle-to-grave environmental performance of polypropylene (PP) kitchenware in the United Kingdom (UK), addressing critical gaps in understanding how material choices, global supply chains, domestic recycling, and consumer use-phase practices interact. Four scenarios were assessed using life cycle assessment (LCA) modelling: virgin PP (vPP) manufactured in China and Germany, recycled PP (rPP) produced in the UK, and a 50:50 vPP–rPP blend. Environmental impacts evaluated using the ReCiPe 2016 Midpoint (H) and IPCC 2021 GWP100 showed that under the modelled scenarios, UK-produced rPP reduces global warming potential (GWP) by about 53% compared with imported vPP, and by 22% compared with UK-manufactured vPP from Germany, driven by avoided virgin polymer production, the absence of long-distance shipping and end-of-life recycling. Toxicity-related impacts revealed trade-offs associated with recycling processes. The rPP product reduced terrestrial ecotoxicity and human non-carcinogenic toxicity by approximately 36% and 16% relative to imported vPP, demonstrating rPP's potential to reduce toxicity-related impacts. Consumer use-phase practices (routine household dishwashing) contributed substantially to lifecycle impacts, becoming the dominant life cycle stage (30-64% of GWP) as material-related impacts were reduced. The study demonstrates that the environmental performance of consumer plastics requires integrated consideration of material systems efficiency, geography, supply-chain arrangements, recycling infrastructure, and consumer behaviour. Such an approach can promote circularity in polymer value chains, with the potential to generate substantial environmental, economic, technical and social benefits.

Keywords Life Cycle Assessment · Recycled Polypropylene · Virgin Polypropylene · Carbon Footprint · Circular Economy · Plastics Recycling

1. Introduction

Global plastic production has expanded rapidly over the past two decades, nearly doubling from its 2000 level over 2000–2019 (OECD, 2022). In 2024, China accounted for 33.3% of total global plastics production, followed by the rest of Asia (19.7%) and North America (17.1%), while the EU27+3 region contributed around 12.3% (PlasticsEurope, 2024b). These regional variations largely reflect petrochemical infrastructure, feedstock availability, and industrial policy. For example, China's polymer expansion has relied largely on

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low-cost coal-based feedstocks, whereas North America's competitiveness stems from access to shale gas resources (IEA, 2024; Larsen and Tilsted, 2024).

Among the most widely used thermoplastics is polypropylene (PP, classified as Type 5), which accounted for approximately 19% of global plastic production in 2023. PP is extensively used in packaging, kitchenware, automotive components and textiles (Hossain *et al*., 2024; PlasticsEurope, 2024a; British Plastics Federation, 2025a), due to its favourable physicochemical properties, including chemical resistance, low density, durability and high thermal stability (Maddah, 2016; British Plastics Federation, 2025a; PlasticsEurope, 2024b; Plastics Recyclers Europe, 2022). Global virgin polypropylene (vPP) production reached approximately 84 million tonnes in 2024, driven by low production costs and high processing efficiency (British Plastics Federation, 2025a; PlasticsEurope, 2024b; Fortune Business Insights, 2025).

The continued reliance of vPP production on fossil feedstocks makes it both energy- and resource-intensive, hence contributing substantially to greenhouse gas (GHG) emissions and the depletion of non-renewable resources (Jones *et al*., 2023). Regional energy systems further shape its environmental performance, as lower-carbon electricity mixes can reduce associated emissions (IEA, 2024). Consequently, vPP production carbon intensity varies significantly across global supply chains, reinforcing the importance of geographical context in environmental impact assessments. At the same time, persistently low recycling rates across regions have placed vPP at the centre of sustainability debates on carbon emissions, waste management, and material efficiency (OECD, 2022; Alliance to End Plastic Waste, 2023).

Recycled polypropylene (rPP) has therefore emerged as a potential alternative that can reduce fossil resource depletion and plastic waste generation (Pinnacle Polymers, 2025). However, the widespread adoption of rPP remains constrained by technical and systemic challenges, such as polymer degradation during reprocessing, contamination from mixed waste streams, and variability in material quality (Alsabri *et al*., 2022; Galve *et al*., 2022; European Parliament, 2024). Empirical studies concur that reprocessing often reduces crystallinity, mechanical strength and thermal stability, thereby limiting rPP's suitability for applications requiring consistent performance (Jones *et al*., 2023; Bernagozzi *et al*., 2024; Chen and Hu, 2024; Velásquez *et al.*, 2024). In addition, inconsistent collection and sorting infrastructure limits recycling scalability in many regions, especially where infrastructure and market incentives remain underdeveloped (Galve *et al*., 2022; Sable *et al*., 2024). Although global rPP production reached an estimated 7.5 million tonnes in 2024, these estimates require cautious interpretation because of limited methodological transparency.

Within the UK, plastic consumption is strongly shaped by international trade dynamics. The UK remains a net importer of both raw and finished plastic goods, representing approximately £13 billion annually in materials, products, and machinery trade (British Plastics Federation, 2025a). In 2023, imports of primary vPP (pellets and granules) and finished vPP goods, such as tableware and kitchenware, originated largely from Germany, Belgium, and Israel, and from China, Turkey, and India, respectively (World Bank, WITS, 2025a, WITS, 2025b, British Plastics Federation, 2025b; Houssini, Li and Tan, 2025). This reliance embeds substantial upstream production emissions and transport-related impacts within global supply chains and contributes to an annual plastics trade deficit of £4.6 billion (British Plastics Federation, 2025b). Because production emissions can account for around 80% of lifecycle GHG impacts (Cullen *et al*., 2020), sourcing decisions (such as domestic rPP production versus imported vPP products) may strongly influence overall environmental performance.

Regional differences in electricity carbon intensity, manufacturing efficiency, transportation distances, and end-of-life (EoL) management practices further complicate these trade-offs (Li *et al*., 2024; PlasticsEurope, 2024a). This dependence increases vulnerability to supply chain disruptions, tariff shifts and changing trade conditions (House of Commons Library, 2020; Department for Business and Trade and Department for International Trade, 2023). Although the UK-EU Trade and Cooperation Agreement (TCA) enables tariff-free trade for qualifying goods, imports from non-EU regions remain subject to global tariff regimes, reinforcing economic and environmental uncertainties associated with international supply chains (HMRC, 2021b; European Commission, 2025).

Policy developments have increasingly sought to address these challenges through circular economy strategies that promote domestic recycling and production capacity. The UK Plastic Packaging Tax, introduced in April 2022, incentivises the use of recycled material by taxing plastic packaging with less than 30% recycled content at £200 per tonne (HMRC, 2021a; British Plastics Federation, 2023). The Extended Producer Responsibility (EPR) scheme introduced in 2025 further requires producers to finance the full net cost of waste collection, sorting, and recycling systems (Ellen MacArthur Foundation, 2021; DEFRA, 2025). Improvements in waste management infrastructure, demonstrated by transitions in municipal systems such as Nottingham's

shift away from landfill and energy recovery towards multi-technology recycling systems (Wang *et al.* 2022), illustrate how policy-driven interventions can enhance material recovery and support domestic recycling capacity. Nevertheless, progress remains slow and limited; the Circularity Gap Report UK estimates that only 7.5% of the UK's economy currently operates on circular principles (Circle Economy, 2023), and the UK remains heavily reliant on imported plastic products, many of which originate from countries where virgin plastics production dominates.

Life Cycle Assessment (LCA), a standardised methodology defined under ISO 14040/44, provides a comprehensive framework for evaluating environmental impacts across material extraction, sourcing, production, use, and EoL management stages (Saleem *et al*., 2023; Nordahl and Scown, 2024). While individual studies have evaluated secondary polyolefin production within specific national or regional boundaries, such as local pellet manufacturing (Saleem *et al*., 2023) or regional supply chains (Alsabri *et al.*, 2022), systematic literature reviews indicate that comparative plastic LCAs remain predominantly focused on single-use packaging or industrial components (Bishop *et al*., 2021; Marson *et al*., 2023). Furthermore, while Nordahl and Scown (2024) highlighted that recycling performance is highly sensitive to regional infrastructure and system design, existing LCA assessments often conceptualise environmental improvements mainly as changes to material sourcing, production processes, and recycling technologies. They rarely integrate interdependencies among international trade logistics (e.g., importing finished consumer products from overseas primary production hubs), domestic consumer use-phase practices, and local EoL recovery systems within a single cradle-to-grave model (Alsabri *et al.*, 2022). However, circularity outcomes are not determined by material flows alone; they emerge from dynamic interactions among production, consumption, and management practices, geographic contexts, and environmental policy mechanisms. A more systemic assessment approach is therefore needed to capture these interconnected factors collectively and how they shape the environmental performance of circular PP pathways.

This study addresses these analytical limitations by integrating material selection, multi-regional production geography (China, Germany, and the UK), spatially explicit transport logistics, and consumer behaviour within a cradle-to-grave LCA of PP kitchenware relevant to the UK market. Specifically, it compares domestically produced rPP with internationally manufactured vPP kitchenware, explicitly accounting for differences in electricity systems, transportation distances, and use-phase practices. A washing-up bowl is selected as a representative case study due to its homogeneous composition, consistent usage patterns, and well-defined EoL pathways (Chen *et al*., 2023; Genovesi *et al*., 2022).

This research advances understanding of the environmental implications of PP circularity through three distinct contributions: (a) integrating consumer household practices into the LCA modelling to address the limited representation of use-phase behaviours on circular polymer systems; (b) extending environmental assessment beyond carbon-centric evaluation by examining performance across 18 midpoint impact categories to identify wider environmental trade-offs associated with PP circularity; and (c) connecting global supply-chain configurations with local recycling systems through geographically explicit life-cycle modelling to assess how regional contexts influence the environmental performance of circular PP pathways, which are currently insufficiently explored. The findings are intended to inform sustainable product design, policy development and investment in domestic recycling infrastructures, supporting the UK's net-zero carbon targets for 2050 (House of Commons, 2024; BEIS, 2021) and broader circular economy transitions (Ellen MacArthur Foundation, 2017; Alliance to End Plastic Waste, 2023).

The paper is organised as follows. Section 2 outlines the LCA methodology used to evaluate environmental impacts. Section 3 presents the results, which are then discussed in Section 4. Finally, Section 5 summarises the key findings and implications for facilitating circular economy transitions within the UK plastics sector.

2. Methodology

The study follows the four-phase LCA framework defined by ISO 14040:2006 and ISO 14044:2006, comprising: i) goal and scope definition; ii) life cycle inventory (LCI); iii) life cycle impact assessment (LCIA); and iv) interpretation. These phases provide a structured approach for evaluating the environmental impacts of products and processes across their life cycle.

Life cycle modelling was conducted in SimaPro 9.5, with background data sourced from the Ecoinvent v3.11 database (system model: cut-off approach (501)). The cut-off allocation approach is adopted, whereby

the burdens of waste collection and sorting are attributed to the product system that generates the waste (i.e., EoL), while the burdens of mechanical reprocessing are attributed to the product system that uses the recycled material (i.e., start-of-life, SoL). No credits for avoided virgin material are applied in any scenario. This approach avoids double-counting and is widely applied in LCA studies of recycled products.

Environmental impacts were assessed using the ReCiPe 2016 Midpoint (H) method, which includes 18 impact categories to provide a comprehensive environmental profile. Global warming potential (GWP) impacts were further evaluated using GWP100 characterisation factors based on the IPCC Sixth Assessment Report (AR6, 2021), to align with current climate science and policy-relevant greenhouse gas accounting (Huijbregts et al., 2017).

2.1. Goal and Scope Definition

This study compares the environmental impacts of vPP and rPP washing bowls manufactured under four supply-chain configurations that vary in geographic origin, polymer sourcing, and material composition. The scenarios assessed, though simplified, are designed to reflect realistic supply chain conditions:

- **Scenario 1:** A washing bowl manufactured in China using 100% domestically sourced vPP and imported to the UK.
- **Scenario 2:** A washing bowl manufactured in the UK using 100% domestically sourced rPP, derived from the processing of clean, post-industrial PP at Biffa's Redcar facility (Biffa, 2025) (see *Supplementary Material* for further details).
- **Scenario 3:** A washing bowl manufactured in the UK using 100% vPP sourced from Germany.
- **Scenario 4:** A washing bowl manufactured in the UK using a 50/50 blend of vPP from Germany and rPP from the UK.

The functional unit is defined as **one washing-up bowl (630 g)**, delivering equivalent washing and soaking functionality over its service lifetime under typical UK household conditions. Functional equivalence between vPP and rPP washing-up bowls is defined based on their ability to perform the intended household function (i.e., containing water and dishes for washing and soaking under typical domestic conditions). Given the low mechanical, thermal, and chemical stress experienced during normal use, minor differences in material degradation or aesthetic properties are not expected to affect functional performance or service life. Accordingly, equivalent service lifetimes are assumed across all scenarios.

A **cradle-to-grave system boundary** is applied that encompasses the following life cycle stages:

- **Raw material extraction and polymer production:** including crude oil extraction, manufacturing (including naphtha production (refining), propylene production (steam cracking), and polymerisation) for Scenarios (1,3,4); and mechanical recycling processes including shredding, washing, sorting, control and extrusion (Scenario 2).
- **Manufacturing (injection moulding):** clamping (securing the mould), injection, cooling, and ejection of finished vPP or rPP product at the respective manufacturing location.
- **Transportation and distribution:** all upstream and downstream logistics required to deliver materials and finished products.
- **Use life (UL) phase:** household use of the washing bowl over its lifetime.
- **EoL management**: within the UK municipal waste system.

Infrastructure processes (e.g., machinery production, facilities, etc.) are excluded to focus on operational material and energy flows.

Scenario modelling involved representative supply-chain configurations. Scenario 1 reflects an international supply chain with virgin polymer production (via naphtha cracking and polymerisation), manufacturing, and packaging occurring in China and distribution in the UK. Scenario 2 represents a domestic UK system based on industrial partner data for recycled polymer production, manufacturing, packaging and distribution. Scenarios 3 and 4 include European polymer sourcing (i.e., Germany) with rail-based transport, manufacturing, packaging and distribution to the UK. At the EoL process, Scenario 1 assumes incineration with energy recovery due to material incompatibility (silicone–PP co-moulding) of the drain plug ring embedded in the bowl, whereas Scenarios 2–4 assume mechanical recycling.

A detailed diagram is illustrated in Figure 1.

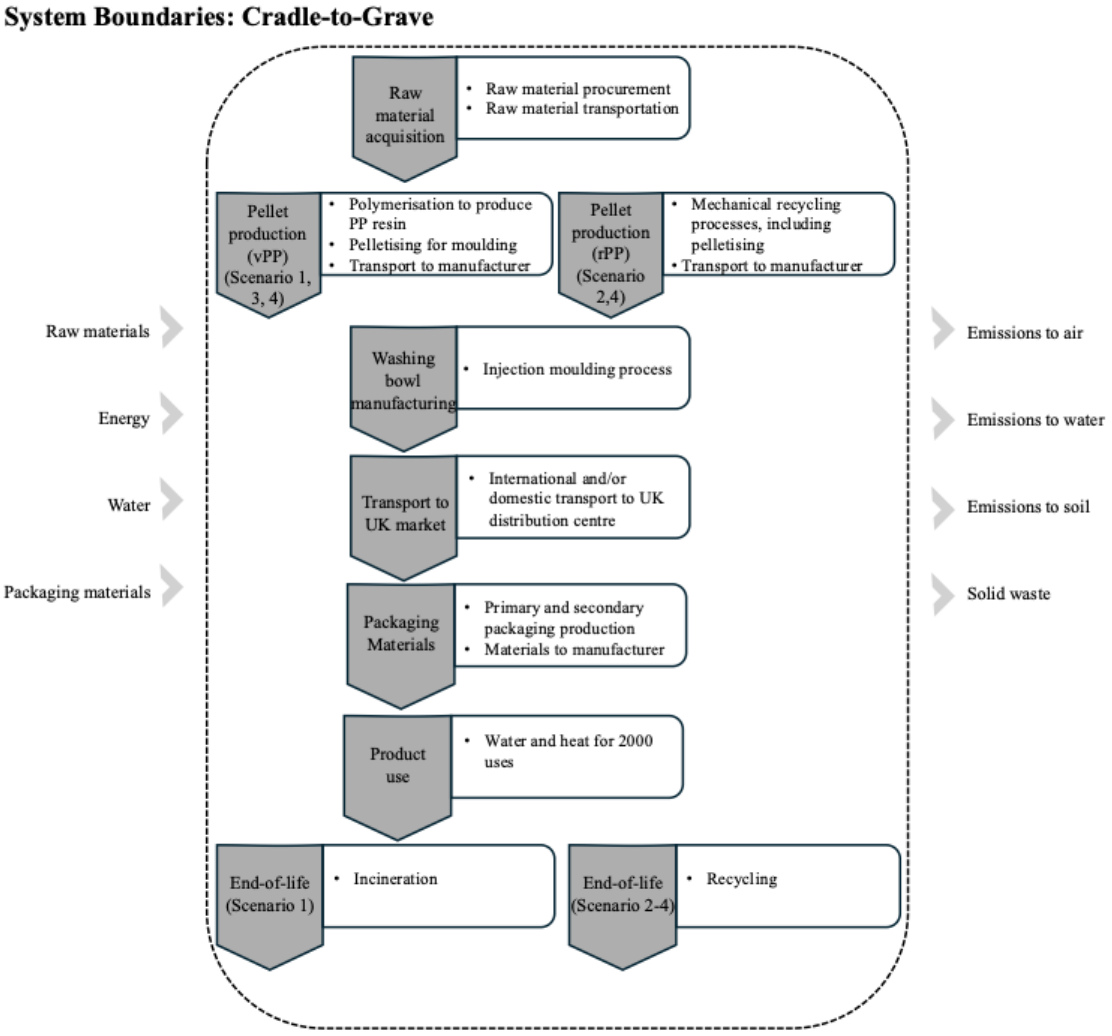


Figure 1. System Boundaries: Cradle-to-grave for all scenarios.

2.2. Life Cycle Inventory (LCI) and Data Sources

The LCI phase compiles and quantifies material and energy flows across all life cycle stages. Inventory modelling is performed in SimaPro 9.5 using datasets from the Ecoinvent v3.11 database, unless industrial partner data were available.

Region-specific datasets were selected where available, including Rest of World (RoW), Europe (RER), global (GLO); national grid electricity for China and the UK was applied in a sensitivity analysis (Section 2.4). Injection moulding processes were modelled using Ecoinvent data, with the RoW dataset used for Chinese manufacturing (Scenario 1), and the RER for UK production (Scenarios 2-4).

Transport emissions were calculated using tonne-kilometre (tkm) values derived from mapped distances and shipment weights. UK road transport was modelled using datasets for > 32-metric-tonne Euro 6 lorries to reflect industrial bulk-transport standards. International logistics were modelled using maritime, rail, and road modes reflecting realistic industrial routes and current emission standards. All logistics assumptions were cross-validated using publicly available data sources. The UK supply chain movements were informed by industrial partner data, including rPP production at Biffa's Redcar facility (Biffa, 2025). Under the cut-off approach, transport of secondary material to the Redcar facility falls outside the system boundary. Subsequent manufacturing was modelled as being executed at PES (Melksham), with packaging provided by Smurfit Kappa (Gosport). The finished product's domestic distribution was modelled via Pointbid (Birmingham). The European supply chain movements assumed vPP production at BASF's Ludwigshafen site, Germany, and distribution to the UK via electric rail using DB Cargo's network (BASF, n.d.).

The use phase (midstream of the value chain) assumes 2,000 washing events over the product lifetime, with 4.5 litres of water per event, resulting in a total of 9,000 litres of water use. This assumption is applied consistently across all scenarios. Energy for heating washing-up water was excluded, as it relates to dishwashing rather than the washing bowl itself.

For EoL management, under the cut-off approach (Scenario 2), the reprocessing burdens of the recycled material used in Scenarios 2 and 4 are assigned at the SoL. At the EoL, the washing bowl in Scenarios 2-4 carries the burdens of collection and sorting at a material recovery facility (modelled using the Ecoinvent dataset for sorting of waste polyethylene as a proxy for PP), while reprocessing is attributed to the next product system. This approach prevents double-counting and provides a conservative baseline for comparison (EarthShift Global, 2019). For Scenario 3 (100% vPP), primary production burdens in Germany are included, and the EoL recycling is treated in the same way as in Scenario 2. The same logic applies proportionally (i.e., for the 50/50 blend) in Scenario 4.

A detailed breakdown of inventory inputs by scenario and life cycle stage is provided in *Supplementary Material, Table S1*.

2.3. Life Cycle Impact Assessment (LCIA)

The LCIA phase translates inventory flows into environmental impact indicators. Environmental impacts were assessed using the ReCiPe 2016 Midpoint (H) method, which includes 18 midpoint impact categories covering climate change, resource depletion, ecosystem impacts, toxicity, and air pollution. The Hierarchist (H) perspective was adopted as it reflects standard scientific consensus regarding impact mechanisms over a 100-year time horizon (Huijbregts et al., 2017). To ensure climate change accounting reflects the latest physical climate science, Global Warming Potential over a 100-year time horizon (GWP100) was additionally evaluated based on the IPCC Sixth Assessment Report, directly aligning climate results with national net-zero policy targets (BEIS, 2021).

A midpoint-oriented approach was selected to avoid value-based aggregation associated with endpoint indicators and to minimise modelling uncertainty by evaluating impacts earlier in the pathway (Huijbregts *et al.*, 2017; Forster *et al.*, 2021). In comparative plastic product LCAs, evaluating multi-indicator midpoint categories is particularly significant for detecting potential burden-shifting across multi-regional supply chains, revealing whether carbon reductions trigger unintended trade-offs in toxicity or fine particulate matter formation during secondary processing and product use. No normalisation or weighting was applied, and results are presented as characterised midpoint indicators. Impact results are reported both as total life cycle impacts and disaggregated by process and life cycle stage to support detailed interpretation.

2.4. Interpretation

The interpretation phase was conducted in accordance with ISO 14044 and includes hotspot analysis, contribution analysis, sensitivity analysis, and consistency and completeness checks to ensure the robustness of results.

a. **Process-level Contribution Analysis:** was performed by disaggregating environmental impacts at both the process level and aggregated life cycle stages, including start-of-life (SoL), use life (UL), and end-of-life (EoL). This enabled the identification of key contributors to environmental impacts across scenarios and supported comparison of upstream, midstream, and downstream contributions.
b. **Sub-system Analysis:** was performed to isolate and compare EoL treatment processes, specifically mechanical recycling and incineration with energy recovery, independently of the system-wide allocation approach.
c. **Sensitivity Analysis:** was carried out using a One-at-a-Time (OAT) approach to assess the robustness of results to key modelling assumptions: (i) the electricity datasets, by replacing the regional background electricity of foreground processes with national grid electricity (China for Scenario 1; 100% renewable electricity for UK processes for Scenarios 2-4); and (ii) the allocation approach, by applying a substitution credit for the recycled content of Scenarios 2 and 4. Sensitivity (i) was additionally evaluated with the use phase excluded, since water use during the product's service life is identical across scenarios and therefore reduces the relative differences between them without altering their ranking.

Consistency was ensured through the application of harmonised system boundaries, functional unit, allocation approach, and data sources across all scenarios. Completeness was verified by including all relevant life cycle stages and impact categories, with additional results for low-contribution categories provided in the *Supplementary Material*.

2.5. Limitations and Uncertainties

A key limitation relates to the modelling of mechanical recycling. Due to the absence of a dedicated PP recycling dataset in Ecoinvent v3.11, a high-density polyethylene (HDPE) recycling dataset was used as a proxy. This approach is supported by literature indicating comparable processing steps and environmental performance (e.g., material retention, energy use, and GHG emissions) between PP and PE recycling systems (Haupt *et al*., 2018; Uekert *et al*., 2023). A dataset for sorting of waste polyethylene was likewise used as a proxy for the EoL sorting of PP. Because the recycling dataset represents post-consumer recycling, which requires more intensive washing than the clean post-industrial feedstock used in Scenario 2, Scenario 2's reprocessing burdens are likely overestimated, particularly for water- and toxicity-related impact categories.

Another limitation is the exclusion of minor components (e.g., drain plug ring) due to a lack of data, which may slightly underestimate impacts. However, given their low mass contribution, the effect is expected to be negligible. Furthermore, Scenario 1 assumes incineration with energy recovery owing to the co-moulded drain plug ring.

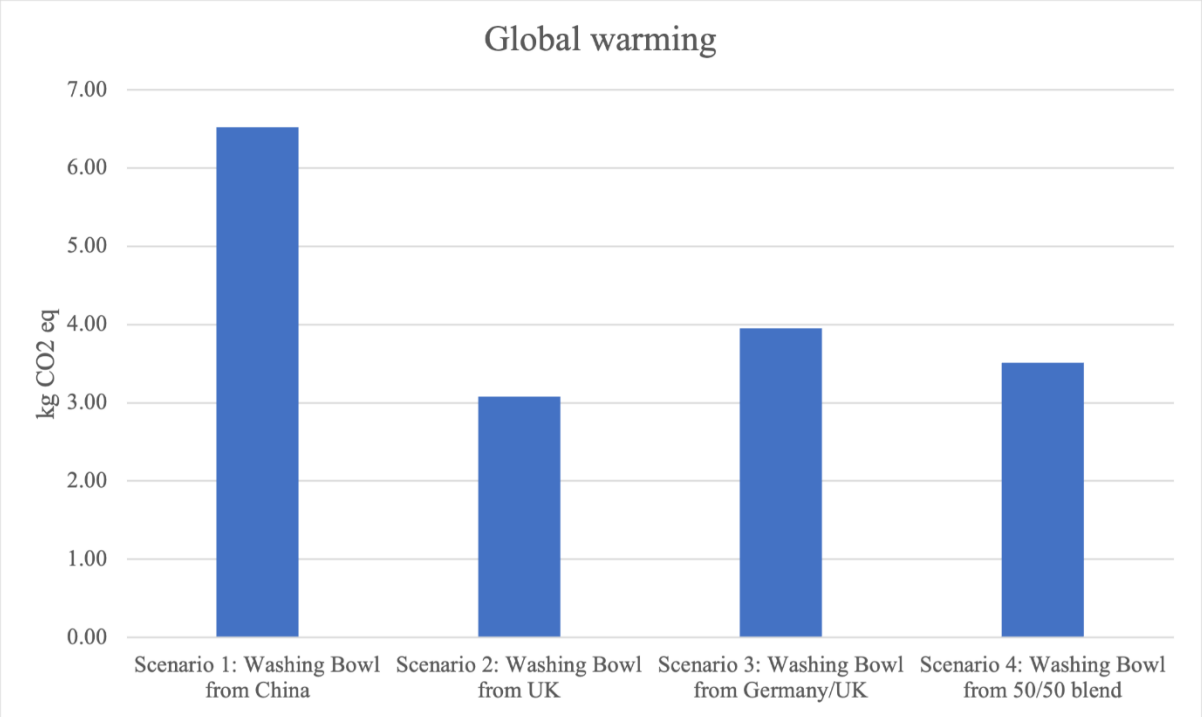
The cut-off allocation approach (Recycled Content method) simplifies EoL modelling; however, it is a widely accepted and methodologically consistent approach in recycled-product LCAs. Pellengahr, Ghannadzadeh, and van der Meer (2023) argue that such simplifications in EoL modelling often fail to reflect real-world complexities. To improve representativeness, the study incorporates spatially explicit transport modelling across the supply chain. This approach achieves a "closer-to-practice" representation and captures facility-level distances and logistics flows. As Kerps *et al*. (2024) note, this representational choice is standard and defensible in product-based LCAs.

The study does not consider potential differences in material durability under more demanding use conditions, as it focuses on a low-stress household product with an equivalent assumed service life across scenarios.

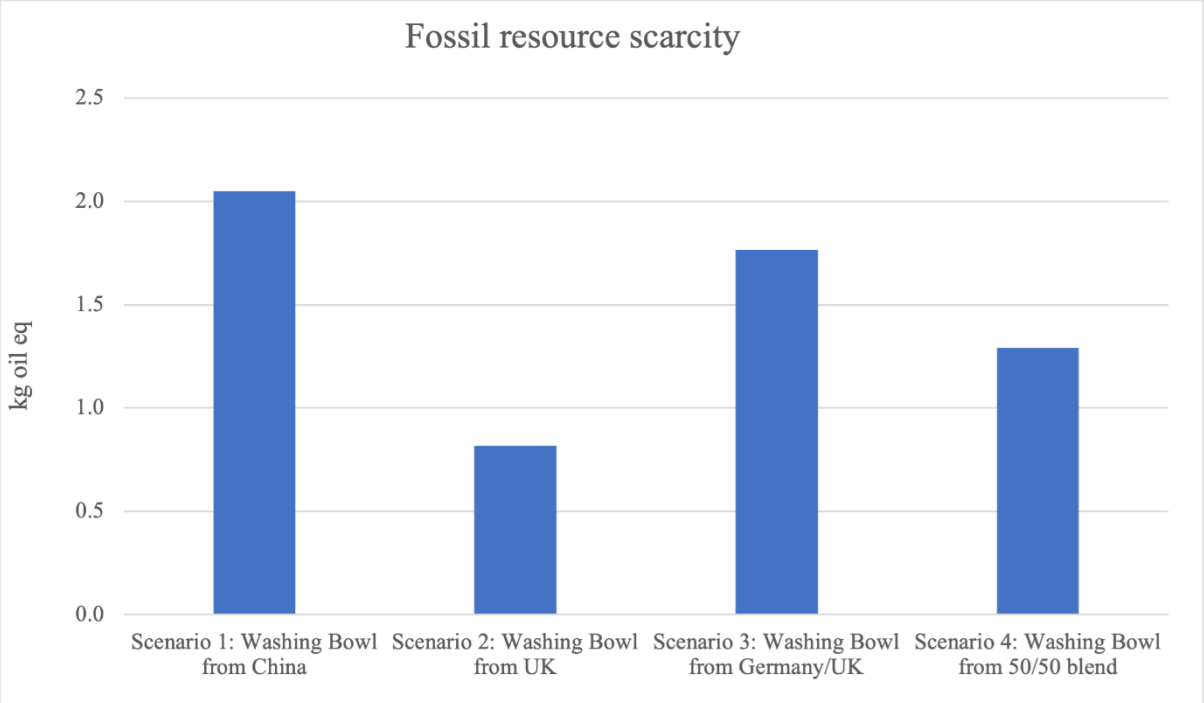
3. Results

Figure 2 (a-c) presents ReCiPe 2016 Midpoint (H) results for the four scenarios, with full numerical results provided in the *Supplementary Material.* Scenario 1 (China manufacturing, 100% vPP) exhibits the highest impacts in most categories. Scenario 2 (UK manufacturing, 100% rPP) shows the lowest environmental impacts in the climate change, fossil resource scarcity and air pollution-related categories, whereas Scenario 3 (Germany, 100% vPP) shows the lowest impacts in the toxicity-related categories. Scenario 4 (50/50 blend, Germany, vPP/UK, rPP) lies between Scenarios 2 and 3 in all impact categories.

Global warming potential (GWP), fossil resource scarcity and land use were identified as the most influential impact categories (Figure 2 a-c). Scenario 1 consistently exhibited the highest impacts, with a GWP of 6.52 kg CO_2-eq, fossil resource scarcity of 2.05 kg oil-eq, and land use of 0.44 m^2a crop-eq per functional unit. Scenario 2 showed substantially lower impacts across these categories, with a GWP of 3.08 kg CO_2-eq (approximately 53% lower than Scenario 1), fossil resource scarcity of 0.82 kg oil-eq, and land use of 0.09 m^2a crop-eq. Scenarios 3 and 4 exhibited intermediate values for GWP (3.95 and 3.51 kg CO_2-eq), whereas land use was similar across Scenarios 2-4.

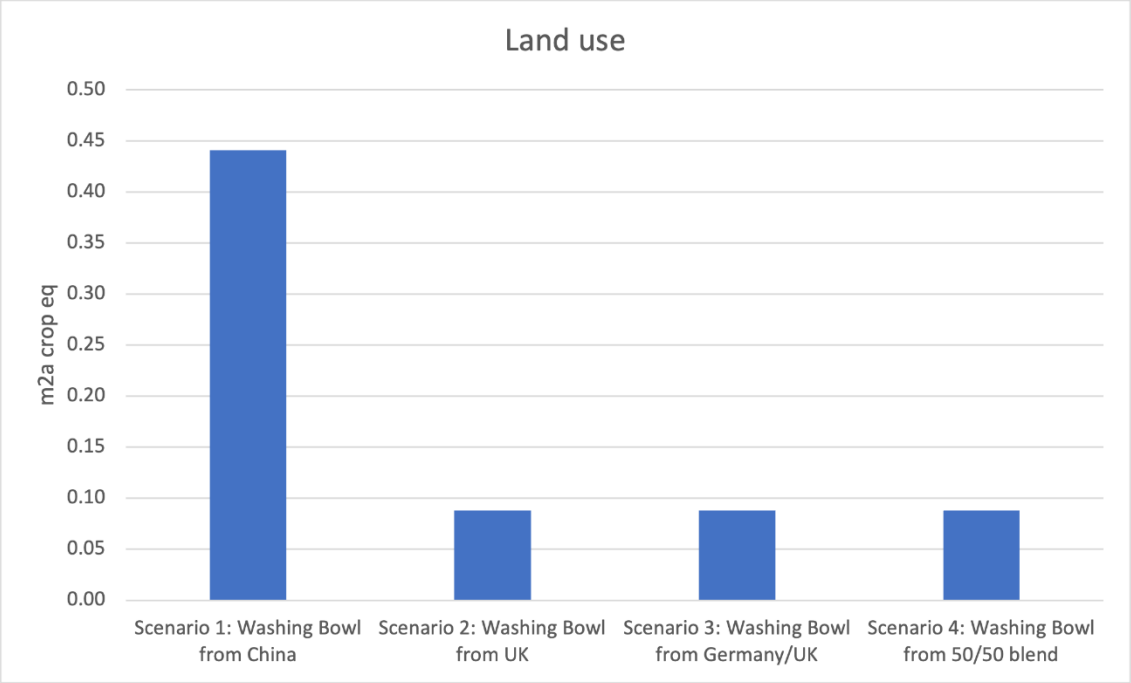


(a)



(b)

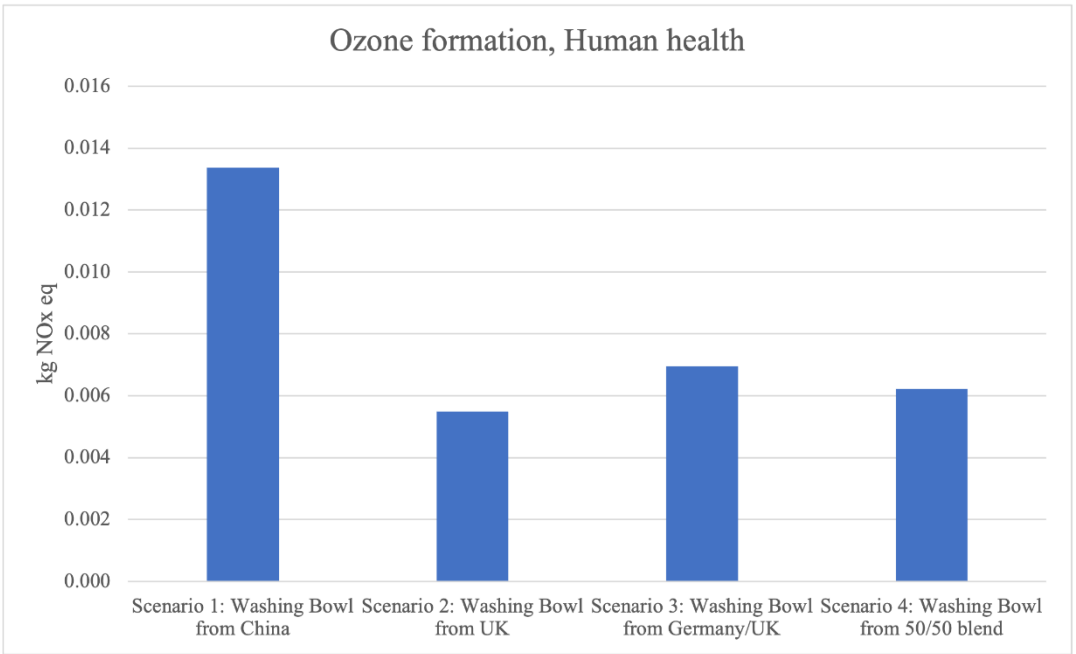
Figure 2. LCA results for ReCiPe 2016 Midpoint (H) method for global warming impact (a), fossil resource scarcity (b) and land use (c) categories across the four scenarios.



(c)

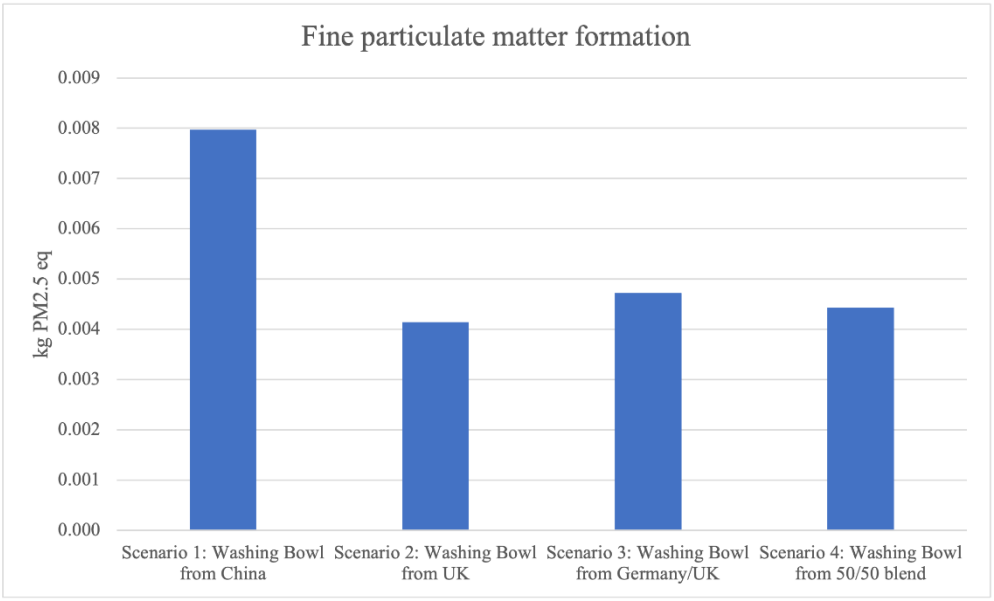
Figure 2 (Cont.). LCA results for ReCiPe 2016 Midpoint (H) method for global warming impact (a), fossil resource scarcity (b) and land use (c) categories across the four scenarios.

Air pollutant-related impact categories, including ozone formation (human health) and fine particulate matter formation, followed a similar trend (Figure 3 a-b). Scenario 1 showed the highest impacts (0.0134 kg NOx-eq and 0.00080 kg $PM_{2.5}$-eq), while Scenario 2 showed substantially lower values (0.0055 kg NOx-eq and 0.0041 kg $PM_{2.5}$-eq), reflecting avoided vPP production and the absence of long-distance shipping. Scenarios 3 and 4 again displayed intermediate results.



(a)

Figure 3. LCA results for ReCiPe 2016 Midpoint (H) method for ozone formation (a) and fine particulate matter (b) impact categories, across the four scenarios



(b)

Figure 3. LCA results for ReCiPe 2016 Midpoint (H) method for ozone formation (a) and fine particulate matter (b) impact categories, across the four scenarios

Toxicity and ecotoxicity categories, including terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, and human toxicity (carcinogenic and non-carcinogenic), varied across all scenarios (Figure 4). Scenario 1 exhibited the highest impacts across all toxicity-related categories, with terrestrial ecotoxicity of 11.20 kg 1,4-DCB and human non-carcinogenic toxicity of 4.35 kg 1,4-DCB. Scenario 2 showed lower impacts in these categories, with terrestrial ecotoxicity and human non-carcinogenic toxicity of 7.19 kg 1,4-DCB and 3.66 kg 1,4-DCB, respectively, corresponding to reductions of approximately 36% and 16% relative to Scenario 1. Scenario 3 showed the lowest toxicity-related impacts (5.50 and 3.13 kg 1,4-DCB), and Scenario 4 falls between the two, indicating that alternative material and processing configurations can also partially reduce toxicity-related impacts relative to Scenario 1.

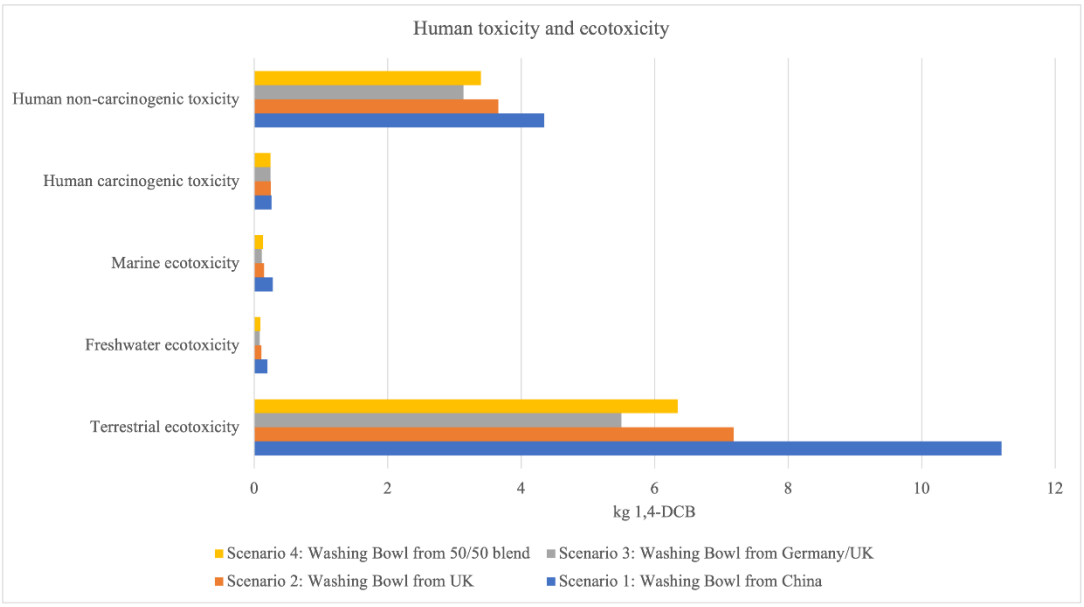


Figure 4. LCA results for ReCiPe 2016 Midpoint (H) method for human and ecotoxicity impact categories, as compared across the four scenarios.

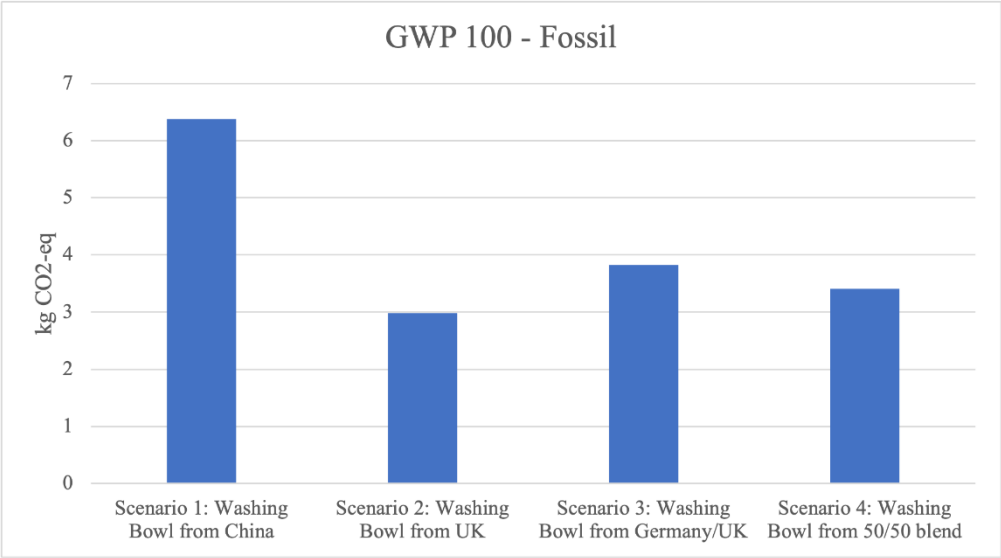
Because the UL phase is identical across scenarios, differences between scenarios arise from material production, manufacturing, transport, and EoL treatment, while UL dominated water consumption. Moreover,

it is worth emphasising that toxicity characterisation is subject to considerable uncertainty, so differences of 15-30% between scenarios should be interpreted with caution. Categories with low absolute values (e.g., stratospheric ozone depletion, ionising radiation, freshwater/marine eutrophication) are reported in the *Supplementary Material*.

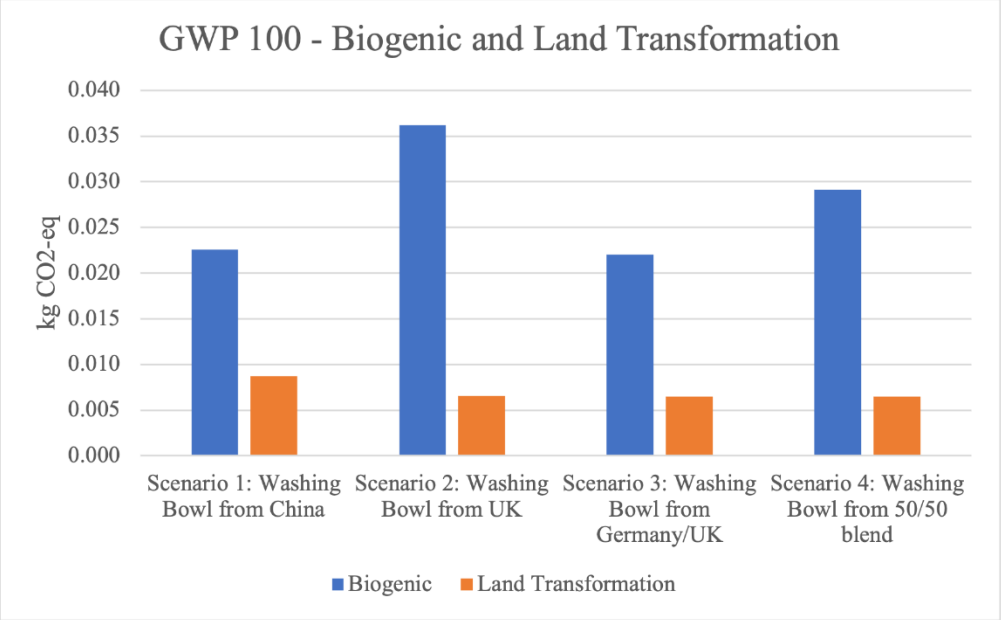
3.1. Climate Change Impacts (IPCC 2021 GWP100)

Climate change impacts were assessed using the IPCC 2021 GWP100 method, with results presented in Figure 5 and detailed values provided in the *Supplementary Material*.

Fossil-based emissions dominated total GWP across all scenarios (Figure 5a). Scenario 1 exhibited the highest fossil GWP, at 6.37 kg CO_2-eq, per functional unit. Scenarios 3 and 4 showed reduced impacts of 3.82 and 3.40 kg CO_2-eq, respectively. Scenario 2 demonstrated markedly lower fossil-based emissions of 2.98 kg CO_2-eq. Full numerical values are provided in *Supplementary Material, Sheet 3*.



(a)



(b)

Figure 5. LCA results for IPCC 2021 GWP100 method for global warming potential 100, fossil (a) and biogenic and land transformation (b) across the four scenarios.

Biogenic and land transformation emissions contributed minimally across all scenarios (Figure 5b). Biogenic emissions ranged from 0.02–0.04 kg CO_2-eq, while land transformation accounted for less than 0.01 kg CO_2-eq. Inclusion of these components did not alter the relative scenario rankings, with fossil-based emissions remaining the dominant contributor across all scenarios.

These IPCC 2021 GWP100 results align with broader trends in the ReCiPe midpoint analysis, confirming that the washing bowl's climate profile is overwhelmingly determined by fossil-based emissions linked to polymer production, manufacturing, EoL treatment, and water supply during the use phase.

3.2. Process-level Contribution Analysis to GWP

Figure 6 presents process-level contributions to GWP. In Scenario 1, product use was the largest contributor (29.9%), followed by EoL incineration (25.2%), pellet production (22.2%), and injection moulding (13.9%). In Scenario 3, product use (49.8%) and pellet production (30.3%) were the main contributors, and Scenario 4 exhibited a similar distribution (56.0% and 21.7%, respectively). In Scenario 2, the use stage accounted for the largest share (64.0%), followed by injection moulding (17.9%) and pellet production (10.6%). EoL collection and sorting contributed 4.1-5.3% in Scenarios 2-4, and transport to the UK market less than 0.5%, compared with 3.1% in Scenario 1. Raw material acquisition is included within the pellet production datasets.

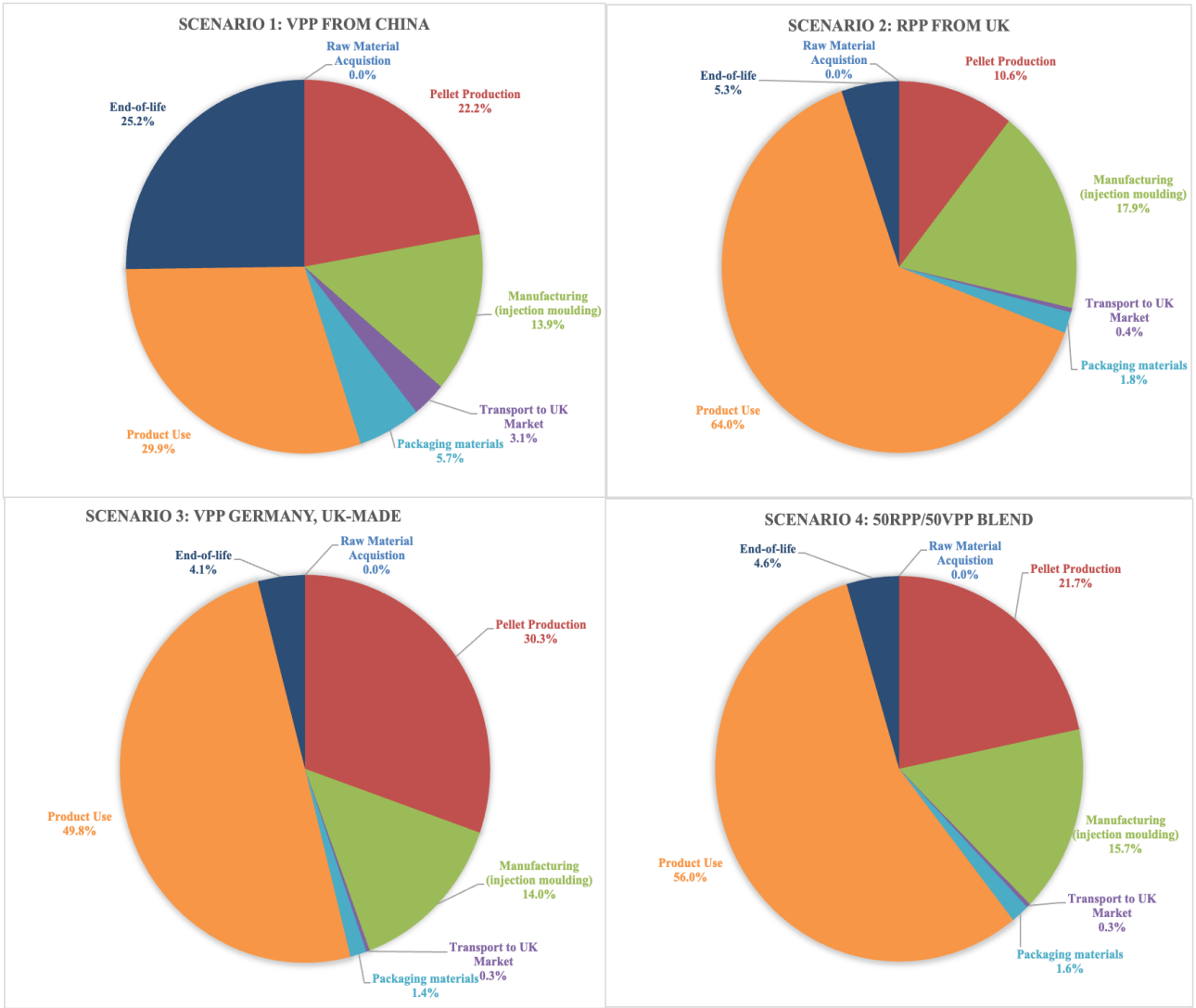


Figure 6. Process-level contribution to GWP of PP washing bowl across four scenarios.

Aggregating processes into life cycle stages (Figure 7) shows that SoL processes dominate impacts in Scenario 1, whereas the UL phase is the largest contributor in Scenarios 2-4, with its relative share increasing as SoL impacts decrease. Specifically:

- **SoL phase (material production, manufacturing, packaging and transport):** vPP production accounts for 44.9% (Scenario 1), 46.0% (Scenario 3), and 39.4% (Scenario 4) of total GWP100 impacts, with pellet production representing 49.5%, 65.9% and 55.2% of SoL impacts. This reflects the energy- and emission-intensive nature of naphtha cracking, polymerisation and injection moulding. In contrast, Scenario 2 avoids virgin polymer burdens by using rPP, reducing its SoL contribution to 30.8% compared with Scenario 1. Long-distance maritime shipping in Scenario 1 contributes notably to climate change and photochemical oxidant formation, whereas Scenarios 3 and 4, which rely on European rail transport, have substantially lower transport contributions. Transport to the UK market is 94.1% lower in Scenario 2 than in Scenario 1.
- **UL phase (use):** contributes to 29.9% (Scenario 1), 64.0% (Scenario 2), 49.8% (Scenario 3), and 56.0% (Scenario 4) of total GWP impacts. The higher relative contribution in Scenario 2 results from its lower SoL burden, not an absolute increase in UL phase impacts.
- **EoL (collection and waste management):** contributes 25.2% in Scenario 1, primarily due to incineration with energy recovery. In Scenarios 2–4, which assume mechanical recycling, the EoL comprises collection and sorting, as the cut-off approach attributes reprocessing burdens to the next product system.

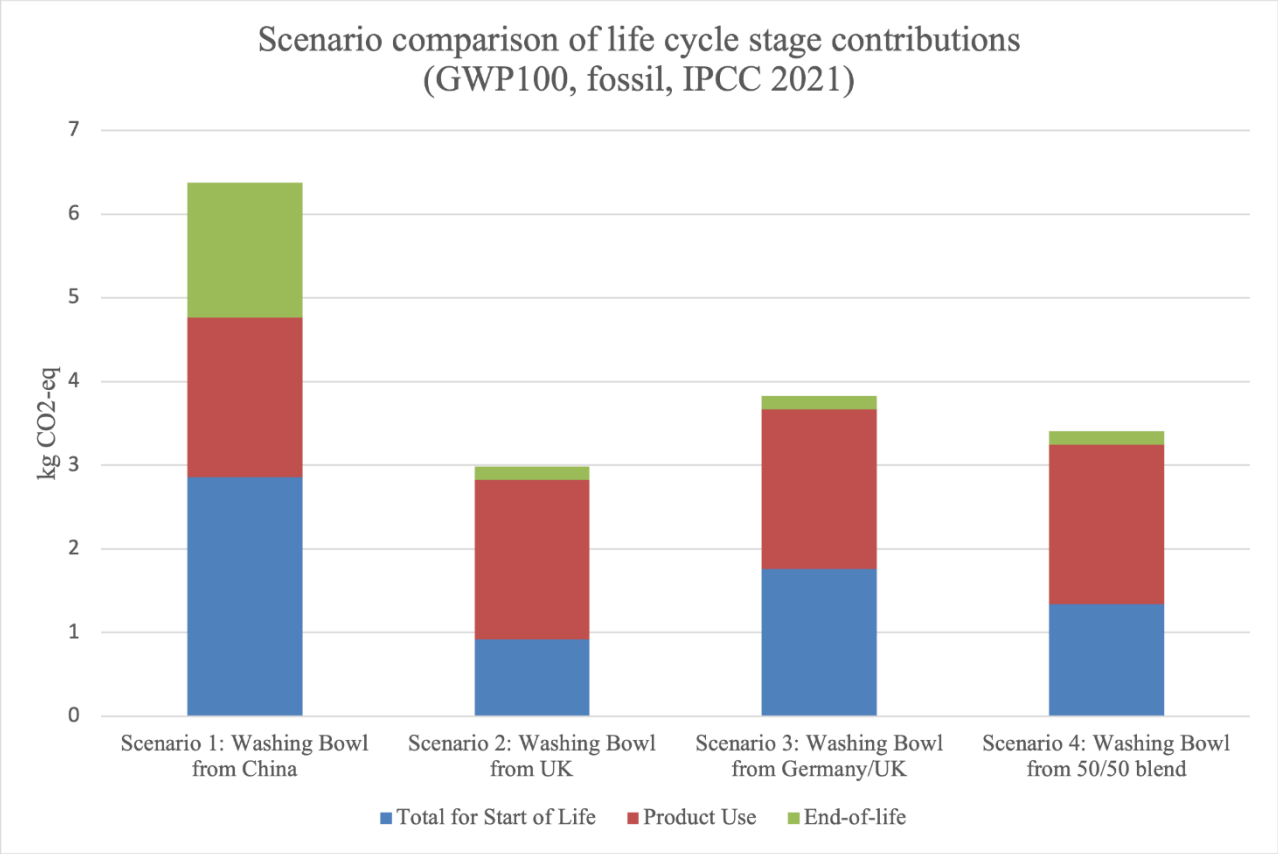


Figure 7. Aggregated contributions of major life cycle stages (start-of-life, SoL; use life, UL; end-of-life, EoL) to the total GWP of PP washing bowls across scenarios. Negative values for Scenario 2 reflect avoided burdens from using rPP, highlighting the climate benefits of material substitution.

3.2.1. Exclusion of the EoL Phase To enable consistent comparison across scenarios, an additional analysis excluding the EoL stage was conducted (Figure 8). Under this condition, SoL processes remained the dominant contributor to GWP in Scenarios 1, whereas the UL phase was the largest contributor in Scenarios 2-4; Scenario 2 retained substantially lower overall impacts.

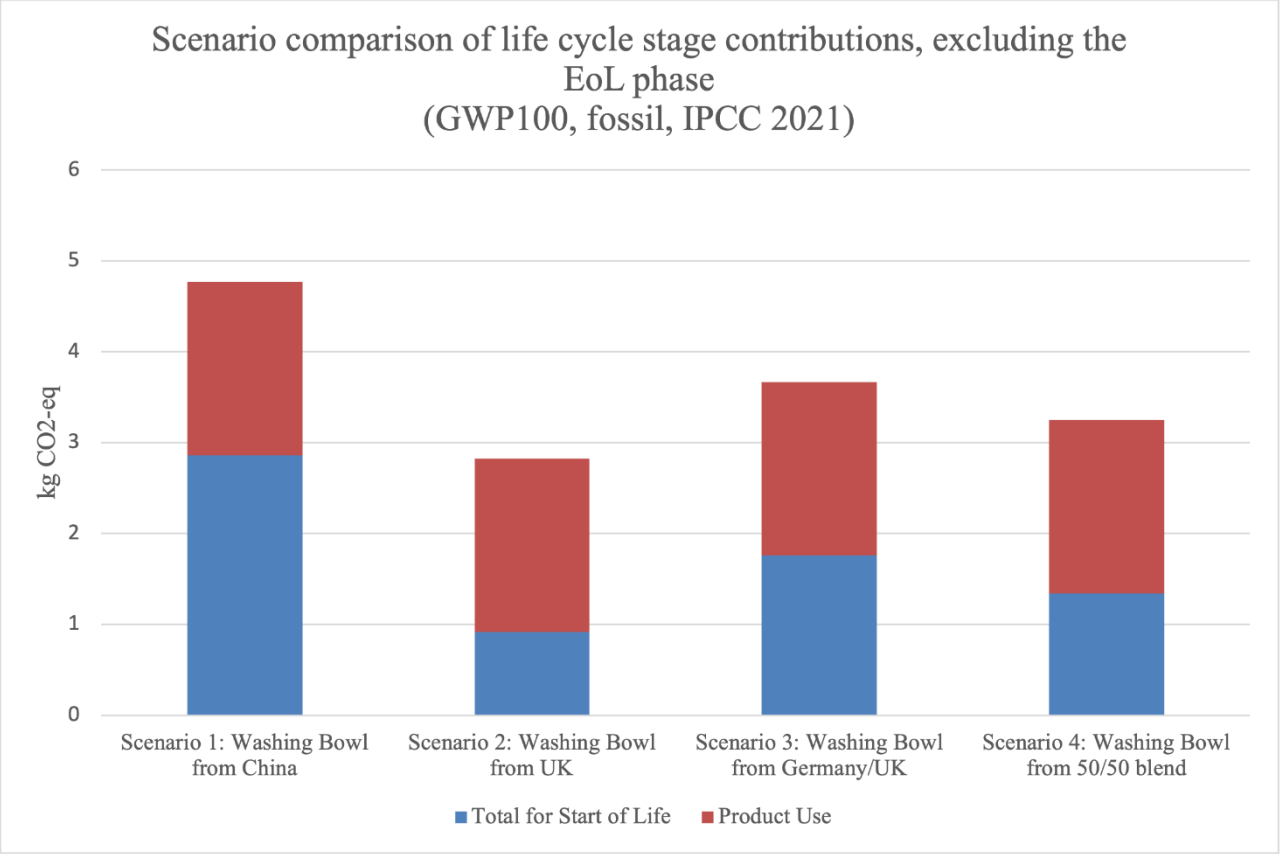


Figure 8. Contributions of life cycle stages to the GWP of PP washing bowls across scenarios, excluding the EoL stage. Negative values represent avoided burdens from rPP, allowing a fair comparison of upstream and use-phase emissions.

3.2.2. Exclusion of the UL Phase Similarly, a scenario analysis excluding the product UL (midstream) phase was conducted to isolate the contributions of SoL (upstream) and EoL (downstream) phases.

- **ReCiPe 2016 Midpoint (H):** Exclusion of the UL phase led to reduced GWP across all scenarios. Scenario 1 decreased from 6.52 to 4.57 kg CO_2-eq, Scenario 2 from 3.08 to 1.13 kg CO_2-eq, Scenario 3 from 3.95 to 2.00 kg CO_2-eq, and Scenario 4 from 3.51 to 1.56 kg CO_2-eq. Without the UL phase, Scenario 2's GWP was about 75% lower than Scenario 1 and 44% lower than Scenario 3. Reductions were observed across multiple impact categories. However, toxicity-related impacts, including terrestrial ecotoxicity and human non-carcinogenic toxicity, remained substantial across all scenarios.
- **IPCC 2021 GWP100:** A similar trend was observed under the IPCC 2021 GWP100 method. Fossil-based GWP decreased across all scenarios. Scenario 1 decreased from 6.37 to 4.47 kg CO_2-eq, Scenario 2 from 2.98 to 1.07 kg CO_2-eq, Scenario 3 from 3.82 to 1.92 kg CO_2-eq, and Scenario 4 from 3.40 to 1.50 kg CO_2-eq. Biogenic and land-use transformation emissions remained low across all scenarios and were not significantly affected by excluding the UL stage.

Detailed numerical results are provided in *Supplementary Material, Sheets 2 and 3*.

3.3. Sub-system Analysis at the EoL stage

A sub-system analysis was conducted to compare the environmental impacts of mechanical recycling and incineration with energy recovery. While SimaPro traditionally allocates reprocessing (mechanical recycling) burdens to the start of a secondary material's life cycle, this sub-system analysis evaluated sorting at MRFs separately and compared it with the incineration process modelled in Scenario 1.

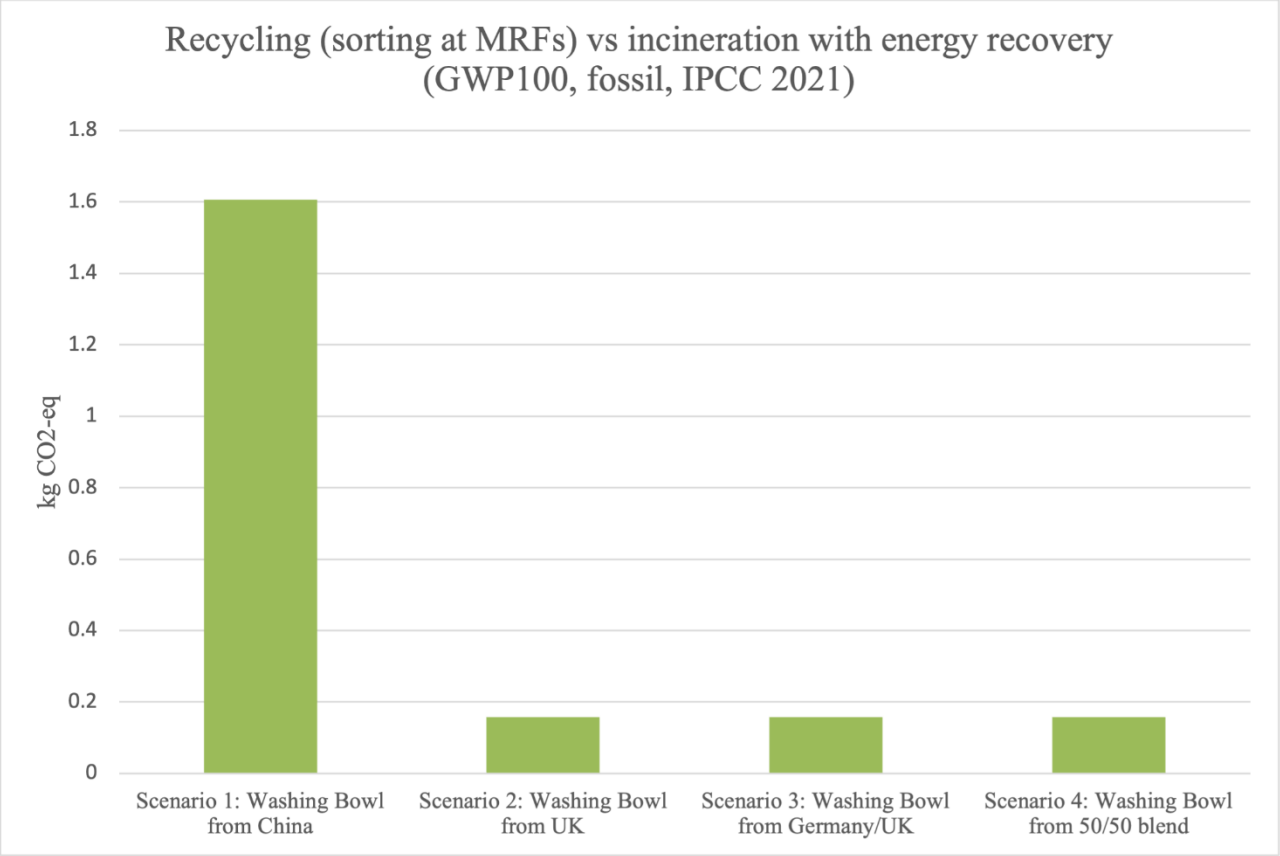


Figure 9. Comparative GWP of isolated EoL sub-systems. The chart illustrates the impact of sorting for recycling (Scenarios 2–4), against the baseline incineration with energy recovery used in Scenario 1.

As shown in Figure 9, the sorting stage (Scenarios 2–4) resulted in a GWP of 0.16 kg CO_2-eq per functional unit, while incineration with energy recovery resulted in 1.61 kg CO_2-eq. This corresponds to a GWP reduction of approximately 90% for the sorting process relative to incineration.

3.4. Sensitivity Analysis: Electricity Datasets and Substitution Credit

To evaluate the robustness of the comparative results, two sensitivity analyses were conducted using a One-at-a-Time (OAT) approach (Supplementary Material, Section E). The first examined how electricity datasets affect the environmental performance of the assessed scenarios. Electricity generation was selected because it represents one of the most influential foreground parameters affecting the LCA assessment in terms of GWP and is subject to substantial regional variation and ongoing decarbonisation efforts. The regional background electricity of processes located in China (Scenario 1) was replaced with Chinese grid electricity, and that of the UK (Scenarios 2-4) was replaced with 100% renewable electricity provision, representing a fully decarbonised UK supply. All other inventory parameters were held constant. The second examined the influence of the allocation approach by applying a 1:1 substitution credit for avoided vPP granulate to the recycled content of Scenarios 2 (0.63 kg) and 4 (0.315 kg).

Applying Chinese grid electricity increased the GWP for Scenario 1, from 6.37 to 6.62 kg CO_2-eq, while applying 100% renewable electricity to UK processes reduced that of Scenarios 2, 3 and 4 to 2.46, 3.42 and 2.94 kg CO_2-eq, respectively, widening the difference between Scenarios 2 and 1 from 53% to 63%. When the use phase was also excluded, the GWP of Scenario 2 was 0.56 kg CO_2-eq per bowl, compared with 4.71 kg CO_2-eq for Scenario 1, an approximately 88% reduction. Under these conditions, Scenario 2 performed better than Scenario 1 in 16 of the 18 ReCiPe midpoint categories, except for marine eutrophication and water consumption.

Applying the substitution credit reduced the GWP of Scenarios 2 and 4 to 1.84 and 2.83 kg CO_2-eq, respectively, increasing Scenario 2's reduction relative to Scenario 1 to 71%. In both cases, the relative ranking

of scenarios remained unchanged, with Scenario 2 consistently exhibiting the lowest GWP and Scenario 1 the highest. This indicates that the study's comparative conclusions are robust to the choice of electricity datasets and allocation approach, whereas the magnitude of the reported benefit is sensitive to both.

Although a probabilistic uncertainty analysis (e.g., Monte Carlo simulation) could provide additional insights into uncertainty propagation, implementing it would require well-defined probability distributions for the life cycle inventory parameters, for which complete uncertainty information was not consistently available. Therefore, a targeted sensitivity analysis was considered the most appropriate approach for evaluating the robustness of the comparative findings.

4. Discussion

This study compared the environmental impacts of PP kitchenware across four scenarios differing by material source (vPP vs rPP) and geographic production context (domestic vs overseas). The results highlight that material selection, supply chain configuration, energy systems and consumer use collectively influence life cycle environmental performance.

4.1. Influence of Material Choice on Environmental Performance

Material selection and supply-chain configuration were identified as the primary determinants of environmental performance across all scenarios. Substituting vPP with rPP substantially reduced GWP, fossil resource scarcity, and air pollution-related categories. Scenario 2 consistently exhibited the lowest impacts in these categories, reflecting avoided primary polymer production. The GWP reduction (approximately 53% relative to Scenario 1) is consistent with previous studies reporting significant benefits associated with mechanical recycling of polyolefins (Yin *et al*., 2016; Galve *et al*., 2022).

Toxicity-related impacts, including terrestrial, freshwater and marine ecotoxicity, as well as human carcinogenic and non-carcinogenic toxicity, showed a more nuanced pattern. Scenario 2 reduced terrestrial ecotoxicity and human non-carcinogenic toxicity by about 36% and 16%, compared to Scenario 1, but exceeded Scenario 3 by about 31% and 17%, indicating that the burdens of mechanical reprocessing and associated transport can offset some of the benefit of avoided virgin production in these categories. Under the cut-off approach, rPP avoids the burdens of virgin polymer production but carries those of mechanical reprocessing (shredding, washing, wastewater treatment, drying and extrusion) and, in Scenario 2, of road transport of the recycled pellets. It therefore performs better where virgin polymer production dominates (climate change, fossil resource scarcity, ozone formation, fine particulate matter and acidification), and worse where reprocessing and transport burden dominates (water- and toxicity-related categories and ionising radiation).

Nevertheless, residual toxicity-related impacts remained across all scenarios, indicating that improvements in material circularity do not necessarily eliminate environmental burdens from chemical emissions in polymer production, plastic additive use, catalyst residues, and waste treatment. Plastics inherently contain a range of additives and residual substances that can leach into the environment and may contribute to ecotoxicity impacts (Casagrande et al., 2024). The findings therefore suggest that increasing the use of recycled material does not necessarily reduce toxicity-related impacts and that complementary measures addressing technologies, chemical inputs, emissions and waste-treatment processes may be needed to achieve further reductions. This highlights the importance of considering chemical management alongside material circularity strategies when seeking to reduce environmental impacts across the plastics value chain.

4.2. Role of Energy Systems, Future Energy Transitions and Geographic Supply Chains

Differences between scenarios highlight the importance of regional electricity mixes and supply chain configurations. Scenarios based on UK and European production (Scenarios 2-4) consistently showed lower GWP than Scenario 1, reflecting differences in regional background datasets, , shorter transport distances, and EoL treatment. The sensitivity analysis showed that applying the Chinese grid electricity to Scenario 1 and

renewable electricity to UK processes widened this difference. These findings align with previous studies identifying the energy grid mix as a key influencer of environmental credits and burdens in plastics production systems (Pellengahr et al., 2023).

Sensitivity analysis indicates that the choice of electricity datasets affects absolute GWP impacts but does not alter the relative ranking of scenarios. Under the decarbonised electricity mix scenario, the rPP-based pathway continued to outperform the vPP-based systems, indicating that material selection and circularity are critical factors of a product's environmental performance, alongside ongoing energy system decarbonisation. The absolute GWP saving of Scenario 2 relative to Scenario 1 is independent of the use phase, which contributes equally to all scenarios (4.16 kg CO_2-eq per bowl under the alternative electricity assumptions, with or without the use phase); excluding the use phase therefore lowers the relative reduction to approximately 88%, indicating the upper range of benefits attainable as UK manufacturing and reprocessing decarbonise.

While all three regions are currently undergoing rapid transitions, the UK and Germany have already achieved clean energy shares of approximately 54.7% and 55.9%, respectively (DESNZ, 2025b; Fraunhofer ISE, 2026), whereas China's grid remains more fossil-heavy with a clean energy share of 38% (Ember, 2026). Combined with the long transport distances, this contributes to comparatively poorer environmental performance of the imported finished plastic products modelled in Scenario 1. These findings demonstrate that improvements in recycling and electricity decarbonisation should be viewed as complementary strategies. Electricity grids may continue to decarbonise, yet the persistence of the scenario ranking in the sensitivity analysis indicates that material selection remains a dominant design decision regardless of future energy transitions.

4.3. Contribution of Life Cycle Stages and Hotspot Identification

Contribution analysis identified polymer production as the dominant source of SoL impacts in vPP-based scenarios (49.5-65.9% of SoL GWP). This is attributed to emissions from energy-intensive processes such as naphtha cracking, monomer polymerisation, and pellet production, which contribute to GWP as well as air pollutants (e.g., ozone and fine particulate matter emissions).

In contrast, the UL phase became the dominant contributor in Scenarios 2-4, especially in rPP scenario (64.0% of GWP), reflecting the reduced upstream burden and the relative importance of downstream processes. This is consistent with previous studies showing that life cycle outcomes, particularly carbon footprint, resource use, and toxicity, can be sensitive to UL phase conditions, contrary to many LCA studies that simplify or omit this stage (Castellani *et al*., 2021; Chen *et al*., 2023). In this study, the UL phase impacts were primarily associated with tap water supply for routine washing; energy for water heating was excluded because it relates to the dishwashing activity and is identical across scenarios, so its inclusion would increase the absolute impacts of all scenarios and further reduce their relative difference without altering their ranking. These results highlight that as upstream manufacturing environmental impacts are reduced through material circularity and decarbonisation efforts, routine consumer practices (e.g., washing frequency, water temperature, and appliance efficiency) can become the dominant source of environmental impact (Fetner and Miller, 2021). This shift emphasises the need for circular economy strategies to extend beyond material production and include product use, consumer behaviour, and household practices, which environmental and sustainability assessments often underestimate (Patsiaouras, 2023). Interventions such as eco-labelling and improved appliance energy efficiency may help reduce these impacts (Nagar and Verma, 2025).

At the EoL phase, recycling performance may also depend on consumer behaviour through handling and disposal, which can alter the overall environmental impact (Cottafava *et al*., 2021). Furthermore, factors such as collection efficiency, contamination rates, and reprocessing energy intensity also influence recycling (Ragossnig and Agamuthu, 2021). In this study, rPP was modelled under conditions of relatively low contamination, representing a best-case scenario.

In practice, however, variations in waste-stream quality and material losses may reduce potential environmental outcomes and savings. Repeated mechanical recycling can degrade polymer properties (due to chain scission and reduced strength), thereby reducing thermal stability and processability and limiting the feasibility of using 100% rPP in high-performance applications (Jones *et al*., 2023; Bernagozzi *et al*., 2024). While additives, compatibilisers, and fillers can partially restore recycled polymer properties (Chen and Hu, 2024; Velásquez *et al*., 2024), fully replacing vPP is not always feasible. Blending strategies, such as the 50/50

mix modelled in Scenario 4, may represent a practical compromise between environmental performance and material functionality.

Evidently, uncertainty hinders the environmental performance of recycled materials and their EoL performance. LCA modelling of the EoL stage of recycled products (mechanical recycling) is subject to data limitations and methodological variability, particularly regarding allocation procedures (Pellengahr et al., 2023). The cut-off approach adopted in this study attributes only reprocessing burdens to recycled materials and applies no credits; applying a credit for recycled content (Section 3.4) increased Scenario 2's GWP reduction relative to Scenario 1 from 53% to 71%. While this method is widely used in LCA studies of plastics, recycling benefits are sensitive to modelling assumptions and may differ under real-world conditions. Addressing these challenges requires both improvements in collection and recycling infrastructure and more detailed LCA modelling to reflect the true complexity of EoL processes.

The sub-system comparison indicates that mechanical recycling has a lower GWP than incineration with energy recovery under the modelled conditions. However, empirical studies indicate that recycling carries real impacts; for instance, Kasper *et al*. (2025) report that high-quality PP recycling typically yields around 85% due to material losses, while the potential microplastic emissions during mechanical drying and wet grinding are notable impacts that deem further exploration (Andrady, 2017; Canopoli *et al*., 2020). Improved process controls can reduce these losses, exemplifying the role of technical and infrastructural innovation and advancement.

The observed shift in dominant life cycle stage across scenarios highlights the importance of system-wide assessment (Iacovidou *et al*., 2021; Gerassimidou *et al*., 2021). Improvements at one stage of the product life cycle (e.g., reductions in upstream impacts with recycled materials) can increase the relative contribution of midstream and downstream processes that may otherwise receive less attention. For instance, transport was identified as a secondary contributor to life cycle impacts, yet its relative importance increases when considered in the context of global trade. This reinforces that the environmental benefits of domestic production through reduced carbon-intensive logistics, while also supporting greater supply chain resilience, are consistent with emerging evidence that regionalisation can enhance the resilience and sustainability of plastics supply chains (Wang *et al*., 2025). Consequently, optimisation strategies focused solely on material substitution risk overlooking opportunities for further environmental improvements through consumer behaviour, logistics and EoL management. These findings reinforce the importance of adopting whole-system perspectives when designing circular economy interventions, recognising that improvements in one part of the system may shift environmental burdens to other life cycle stages rather than eliminate them (Iacovidou et al. 2021).

4.4. Implications for Circular Economy Strategies and Policies

The findings support that increasing the use of recycled material can reduce environmental impacts in plastic products. However, the magnitude of these benefits depends on system conditions, including energy sources, recycling efficiency and consumer behaviour, within the system boundaries and assumptions defined in this study. For instance, domestic rPP production may offer environmental benefits under the UK's increasingly decarbonised electricity mix (50.4% renewables in 2024, with coal fully phased out) (DESNZ, 2025a; Houssini *et al*., 2025), with the sensitivity analysis indicating further gains under a fully renewable electricity supply and through targeted recycling of specific waste streams.

However, fragmented waste collection systems and high contamination in post-consumer recycling streams may currently limit achievable performance (Holmes *et al*., 2023). Forthcoming improvements in collection, sorting, and processing infrastructure may support higher-quality recycled material production (DEFRA, 2025; Sambyal *et al*., 2024). Policy instruments such as the UK Plastic Packaging Tax currently incentivise recycled content, but their scope could be expanded to other consumer goods, helping to translate technical potential into measurable multidimensional impacts and net savings (Nagar and Verma, 2025). Similarly, emerging Extended Producer Responsibility (EPR) policies, including those promoted through the UK Plastics Pact, signal a broader move toward placing greater accountability on the producers for the lifecycle impacts of the materials they introduce to the market (WRAP, 2024). Effective governance could ensure these measures are coordinated, enforced, and supported by investment in collection, sorting, and reprocessing infrastructure.

At present, however, cost competitiveness remains a structural challenge, particularly where imported goods produced at scale and at lower cost can undercut domestic rPP products, even where, as in the scenarios

assessed here, they carry higher environmental burdens. Without protective measures, UK industries face competitive disadvantages under carbon pricing schemes (Keen *et al*., 2022; Kurz and Rubínová, 2024). Mechanisms such as carbon border adjustments and green public procurement can internalise environmental costs into product prices, stimulate domestic production and shift demand toward low-impact options (World Economic Forum and Boston Consulting Group, 2022).

Scaling domestic rPP production could not only reduce carbon-intensive imports but also create local jobs, spur new business models, and deliver social value as consumers increasingly recognise and prefer locally produced goods. However, increasing recycled content alone is unlikely to maximise environmental benefits. Policies should actively promote repair, reuse, and product longevity, while supporting electricity decarbonisation, efficient collection systems, and high-performing recycling infrastructure to prevent unintended consequences, such as creating artificial demand for recyclable plastics that could inadvertently reinforce virgin polymer production and perpetuate existing linear plastic production systems. Such an integrated approach prevents pervasive lock-ins and establishes a balanced approach that promotes and strengthens circular economy strategies.

Overall, this study shows that environmental performance is governed by interactions among material selection, electricity generation, supply chain configuration, and consumer behaviour rather than by any single intervention. Although increasing rPP content provides the greatest reductions in climate-related impacts under the conditions assessed, the results also demonstrate that these benefits are strengthened by electricity decarbonisation and supported by efficient collection and recycling systems. The findings therefore suggest that effective circular economy strategies require coordinated interventions across material production, energy provision, waste management and product use systems, rather than isolated improvements focused on individual stages of the product life cycle.

5. Conclusions

This study presents a cradle-to-grave life cycle assessment (LCA) of polypropylene (PP) kitchenware, using the washing bowl as a case study, to examine how material sourcing, geographic production context (domestic vs. overseas), supply chain configuration, use-phase practices and end-of-life (EoL) pathways influence the environmental performance of circular plastic systems. Across four scenarios representing virgin and recycled PP (vPP and rPP) produced domestically and overseas, the findings show that rPP generally outperforms vPP, particularly in global warming potential (GWP) and fossil resource depletion. The UK-based rPP scenario showed the lowest GWP, achieving a reduction of about 53% (baseline) and 88% under the UK decarbonised grid and uselife (UL) phase exclusion compared with the modelled overseas vPP scenario. Moreover, environmental gains are highly context-dependent and influenced by energy systems, consumer use-phase practices, recycling conditions, material quality, and supply-chain characteristics. For instance, the post-consumer recycling dataset used as a proxy likely overestimates mechanical reprocessing and transport in Scenario 2.

Beyond demonstrating the benefits of rPP use, the study advances the conceptual understanding of polymer circularity by showing that environmental performance emerges from interactions across the entire value chain rather than from upstream material substitution alone. By incorporating consumer use-phase practices within the cradle-to-grave framework, the study highlights the importance of considering midstream dimensions, alongside upstream and downstream circularity interventions. Furthermore, by evaluating multiple midpoint impact categories, the study demonstrates the need to move beyond carbon-centric assessments and consider potential environmental trade-offs associated with circular strategies. Finally, by linking global production networks with local recovery systems, the study conceptualises recycled polymer pathways as geographically embedded systems in which supply chains, energy, and waste management infrastructures jointly influence environmental outcomes.

These insights challenge the prevailing assumption that increasing recycled content or reducing production-related emissions is a sufficient indicator of circularity performance. Instead, they demonstrate that circular polymer transitions require a systemic approach that accounts for environmental, infrastructural, policy, geographical, and behavioural dimensions simultaneously. Such an approach provides a more comprehensive basis for evaluating whether circular economy strategies deliver meaningful and sustained environmental improvements. Several limitations should nevertheless be noted. Mechanical PP recycling was modelled using

an HDPE proxy dataset because of data constraints in Ecoinvent v3.11, and minor low-mass components (such as the drain plug ring) were excluded. Furthermore, the study applied a simplified cut-off allocation for EoL accounting and assumed equivalent service life across scenarios without evaluating material durability under high-stress conditions.

From a policy perspective, the study highlights that improving the circularity of the PP product system requires coordinated action across the entire value chain. While recycling represents an important pathway toward reducing the environmental burden of plastics, its effectiveness depends on overcoming structural challenges, including inconsistent feedstock quality, limited domestic processing capacity, fragmented collection systems, and competition from lower-cost virgin polymers. No single intervention can deliver circularity in isolation. Instead, achieving optimal environmental outcomes requires integrated strategies across three interdependent areas: (i) investment in collection, sorting and reprocessing infrastructure to secure a reliable, high-quality feedstock, (ii) governance mechanisms and market incentives to support competitiveness of recycled polymers, and (iii) behavioural interventions that address use-phase impacts and encourage sustainable consumption practices. These measures combined can support the transition towards a resilient, circular, resource-efficient and low-carbon plastics economy.

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Author Contributions CJ: methodology, software, validation, formal analysis, investigation, resources, data curation, writing—original draft preparation, visualisation; JA: software, data curation, validation; KSN: software, validation, writing—review and editing, resources; KQ: experimentation, validation, writing—review and editing; GF: project administration, funding acquisition, writing—review and editing; EI: conceptualisation, validation, resources, supervision, funding acquisition, formal analysis, investigation, resources, data curation, writing—original draft preparation, writing—review and editing, visualisation. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement Supporting data and the LCA calculation files are provided in the supplementary materials. Primary data used in the assessment were provided by ReBorn, UK and Biffa Polymers. The data sources and life cycle inventory datasets used in the assessment are identified in the manuscript and supplementary materials. Proprietary datasets, including ecoinvent data, cannot be redistributed and remain subject to the terms and conditions of the respective data providers. Additional information required to reproduce the analysis is available from the corresponding author upon reasonable request.

Declarations

Competing Interests The authors declare no competing interests.

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