ADDITIVES IN PLASTIC MANUFACTURING AND IMPLICATIONS FOR MECHANICAL RECYCLING

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Abstract. Additives are widely used to improve the performance of plastic resins, enhance processability, and enable products to meet application-specific requirements. However, their contribution to plastics' life-cycle assessment (LCA) is often overlooked. Additionally, some additives are regulated due to health and toxicological concerns, which can restrict their use and hinder the recycling of plastic products. Minimizing additive loading to the levels necessary for technical performance could also improve plastic recyclability. This study reviews the literature on common additives used in major plastic resins and discusses the results of an LCA of representative additives—such as plasticizers, flame retardants, stabilizers, scavengers, and pigments—by incorporating them into the formulations of PVC and PET products. Based on the current analysis, considering prevalence in plastics, typical loadings, environmental and health hazards, global production and consumption, and recycling implications, plasticizers, flame retardants, pigments, and stabilizers have been identified as the most consequential additive groups. The analysis aims to provide insights into environmental metrics such as greenhouse gas (GHG) emissions, fossil energy use, and water consumption in plastic formulations. The findings indicate that, compared with PVC without additives, certain additives increased product GHG emissions by roughly 0.3% to 25%. Across all cases, the additives' mass fraction had a greater influence on GHG outcomes than their inherent emission intensities. Additionally, a hypothetical analysis was conducted on the PET supply chain flows caused by hypothetical variations in material flow parameters, including the loading rate of additives, recycling rate, etc. Results indicate that increasing the recycling rate of post-consumer PET bottles, along with their allocation for closed-loop (bottle-to-bottle) recycling, could raise the recycled content in mechanically recycled PET bottles by up to 12%, resulting in an 8% reduction in virgin PET consumption. However, other variables, such as sorting yield, could be incorporated into the analysis to refine these findings. Overall, this study provides a framework for assessing the environmental impacts of plastic additives and their influence on product emission footprints. It also explores how variations in material flow factors and parameters—hypothetically affected by additive mass fractions—could alter material recovery for recycling.

Keywords: life-cycle assessment (LCA), plastics, additives, mechanical recycling.

Introduction and Motivation

Plastic waste management has drawn increasing public attention as growing volumes of plastics are landfilled, combusted, or leak into the environment due to mismanagement. Although recycling technologies—from mechanical methods to advanced options (e.g., pyrolysis, gasification, methanolysis, enzymatic hydrolysis)—offer pathways to mitigate plastic end-of-life (EOL) impacts, recycling rates remain low (e.g., <9% in the U.S.),[1] and mechanical recycling is still the predominant practice.[2] Efforts to scale recycling face multiple constraints, including inadequate collection and processing infrastructure; limited markets for recycled content; incomplete understanding of product chemistries; degradation of mechanical properties; inconsistent product quality; high contamination; and economic barriers affecting both the recovery of plastics and the use of recycled materials in new products.[3] The sector's emphasis on performance improvements—largely through the development and use of additives—introduces additional challenges for mechanical recycling. While additives enhance the mechanical and physicochemical properties of resins, they are difficult to remove from the base polymer due to low molecular diffusion rates[4] and uncertain or variable additive compositions. For example, a major challenge for mechanically recycled polyvinyl chloride (PVC) is its high additive content (e.g., plasticizers incorporated during production to achieve desired properties),[4] some of which are considered hazardous chemicals. The relative importance of these drivers remains poorly understood and warrants further research.

This paper summarizes the results of our previous work by Gracida-Alvarez et al.[5] on common additives used in two major resins—polyethylene terephthalate (PET) and polyvinyl chloride (PVC)—and expands the analysis to evaluate the potential environmental burdens and recycling implications of selected additives using life-cycle assessment (LCA). PET is widely considered the most recyclable plastic, whereas PVC formulations often contain the greatest diversity and highest mass fractions of additives. We present cradle-to-gate LCA results that incorporate additives into PET and PVC formulations across different applications, quantifying how additives can influence environmental impacts and the recyclability of plastic products. Although Gracida-Alvarez et al.[5] focused on PVC effects of additives in different applications, here we extend the same approach to PET for bottle application. The environmental metrics considered include greenhouse gas (GHG) emissions and fossil energy use. As part of this effort, data on the material and energy requirements of five additional PET additives were collected and analyzed. We also propose a conceptual framework using material flow analysis (MFA) to examine how material-flow factors—potentially influenced by variations in additive concentrations—affect the mechanical recycling of PET bottles. While the MFA quantifies plastic and additive flows across life-cycle stages, these quantified flows directly inform key LCA inputs (e.g., material amounts processed, recycled, and disposed). Therefore, to understand the magnitude and pathways of plastic flows, it is necessary to parameterize the LCA and to interpret the resulting environmental impacts. Finally, to address circularity, we report results for solid waste generation and virgin material use.

Review of Related Work

Many LCAs of plastic resin production and recycling technologies have been published; a comprehensive review is provided by Gracida-Alvarez et al.[5] However, the treatment of additives—their types and impacts—within LCAs remains limited. This gap stems in part from scarce processing data for additive manufacturing and restricted access to formulation mass fractions, which are often proprietary. Several authors have emphasized the value of explicitly including additives in life-cycle inventories (LCIs).[6] This is especially important when formulations contain multiple additives, to ensure that cumulatively significant environmental burdens are not overlooked. Our previous work[5] identified four key additive groups through a mapping exercise that involved the commonalities of over 15 additive groups in different characteristics such as global production rates and consumption volumes, mass fraction in resin, popularity and use, and potential causes of health and environmental issues. This exercise organized the most representative additive groups for each characteristic into a decision diagram, which results in four most prevalent additive groups within each characteristic: plasticizers, flame retardants, colorants and pigments, and stabilizers. Additionally, our evaluation for PET included four additional additive groups. Oxygen and acetaldehyde scavengers, along with fast reheat and catalyst, are additives commonly used in PET, serving an important role, especially in beverage packaging applications. From each group, we studied the material and energy requirements to manufacture selected and most representative additive chemicals, as shown in Table 1.

Table 1. Additive chemicals used in plastics for the key additive group

Group	Chemical	Group	Chemical
Plasticizer*	Di-2-ethylhexyl phthalate (DEHP)	Oxygen scavenger	Nylon MXD6
	Di-isononyl phthalate (DINP)		
Flame retardant*	Tetrabromobisphenol-A (TBBPA)	Acetaldehyde scavenger	Anthranilamide
	Decabromo diphenylether (decaBDE)		
Pigments/ Colorants	Lead- chromate*	Fast reheat	Carbon black
	Chromium trioxide*		
	Titanium dioxide		
Stabilizers*	Barium nonyl phenate (heat stabilizer)	Catalyst	Antimony trioxide
	Benzophenone (Light stabilizer)		

Note: *adapted from Gracida-Alvarez et al.[5] MXD: m-xylelene diamine

Both Di-2-ethylhexyl phthalate (DEHP) and Di-isononyl phthalate (DINP) are used as a plasticizer for PVC. DEHP annual global production is estimated to be between 4.5 to 22 thousand tonnes (kt),[7] while DINP is estimated to be between 45 and 113 kt.[8] Tetrabromobisphenol A (TBBPA) is a flame retardant employed across plastics, paper, and textiles. Its annual production ranges from 9 to 45 kt, and approximately 90% is incorporated into plastics as an additive.[9] Decabromodiphenyl ether (decaBDE) is broadly used as a brominated flame retardant in plastics, textiles, and adhesives, with annual output estimated at below 0.5 kt.[10] Lead chromate is a common yellow pigment used in applications including plastics and inks, with an estimated annual production capacity of less than 0.5 kt.[11] Chromium trioxide serves as a popular color additive in various products, with its production capacity estimated between 23 to 45 kt per year.[12] Titanium dioxide is a white pigment widely used across several sectors, with plastics accounting for 23% of its consumption. Its annual production is estimated to range between 450 and 2,230 kt.[13] Barium nonylphenate primarily functions as a heat stabilizer in PVC; it is also used in the production of lubricants, surfactants, and fungicides. Annual production is less than 0.5 kt.[14] Benzophenone is commonly used as a UV blocker in plastics with an annual production of approximately 450 kt.[15] Nylon MXD6, known for its excellent barrier properties, is used as an agent to preserve the freshness and stability of products in the food and pharmaceutical industries.[16] Anthranilamide reacts with acetaldehyde generated during PET degradation, minimizing its presence in the products stored within PET containers.[17] Its annual production is less than 450 kt.[18] Finally, fast reheat additives (carbon black) and catalyst (antimony trioxide) were also included in the analysis for PET formulations.[19,20] Detailed information about the manufacturing of most of these additive chemicals and the production inventory can be found at Gracida-Alvarez et al.[5] We used the additive-chemical life-cycle inventories to evaluate cradle-to-gate LCAs for several application pathways, including PVC products—vinyl flooring, window frames, insulation, sewer pipes, and cable coatings—which represent the highest production volumes in the United States. Additionally, we evaluated PET bottles with additives, a prominent product in PET applications.

As the second part of this work, we focus on understanding how additives affect recycling streams. Tracking additives—particularly in mechanical recycling—is essential, as plasticizers, flame retardants, and pigments can alter the physical and chemical properties of the recycled resin. Systematic tracking helps ensure that recycled materials meet specifications for their intended applications and mitigates degradation-related losses in performance. On the other hand, some additives, such as certain flame retardants or heavy metal-based pigments, may pose health and environmental risks. Tracking these additives ensures compliance with safety regulations and standards, such as Registration, Evaluation, Authorization, and Restriction of Chemicals (REACH) or Restriction of Hazardous Substances (RoHS).[5,21,22]

Analysis Approach

A product-level LCA was performed for PVC and PET to assess the potential impacts of the inclusion of additives in the resin formulation for different products. LCA provides a comprehensive view by analyzing energy use, resource consumption, emissions, and waste generation throughout the PVC and PET life cycle. In the first part of this work, we focused on the emissions and fossil energy use from raw material extraction to manufacturing, also known as cradle-to-gate analysis, of five PVC products – vinyl flooring, window frames, insulation, sewer pipes, and cable coating, and one PET product – PET bottle – The selection of these products was based on U.S. production levels.[3,5] We used the R&D GREET version 2023 for this analysis,[23] and the methodology adheres to the same principles employed in the LCA carried out for additives. The analysis assumed that the eleven additives identified above were used in the formulation for these products. The life cycle inventory of PVC and PET can be found elsewhere,[23,24] while Table 2 summarizes the average mass fraction of additive groups applied to PVC and PET example products.

Table 2. Average mass fraction of additives and resin in different examples of PVC and PET products.[5,25,26]

Resin	PVC					PET
Application	Vinyl flooring	Window frame	Insulation	Sewer pipe	Cable coating	Bottle
Filler	31.2 %	4.4 %	13.2 %	4.3 %	24.0 %	N/A
Plasticizer	18.0 %	-	27.1 %	-	24.5 %	N/A
Flame retardant	-	-	0.4 %	-	-	N/A
Stabilizer	1.9 %	3.7 %	3.1 %	1.8 %	2.3 %	0.2 %
Pigment	1.6 %	3.0 %	-	0.4 %	0.5 %	1.1 %
Oxygen scavenger	N/A	N/A	N/A	N/A	N/A	1.0 %
Acetaldehyde scavenger	N/A	N/A	N/A	N/A	N/A	0.1 %
PVC resin	43.2 %	68.7 %	56.0 %	93.1 %	48.0 %	N/A
PET resin	N/A	N/A	N/A	N/A	N/A	97.6 %

N/A: non-applicable

To understand the implications of additives and loading rate in the mechanical recycling of plastics, Gracida-Alvarez et al.[5] developed an approach that uses MFA in conjunction with LCA to determine the end-of-life and recycling flows, as well as the circularity metrics associated with varying quantities of additives used in PET MFA allows for the tracking of not only additives, but also raw materials, losses, and recycled outputs throughout the supply chain of the product. This ensures a clear picture of how materials are transformed. Figure 1 shows the life cycle of PET production from the polymerization of monomers ethylene glycol (EG) and purified terephthalic acid (PTA) to bottle manufacturing, and mechanical recycling.[24]

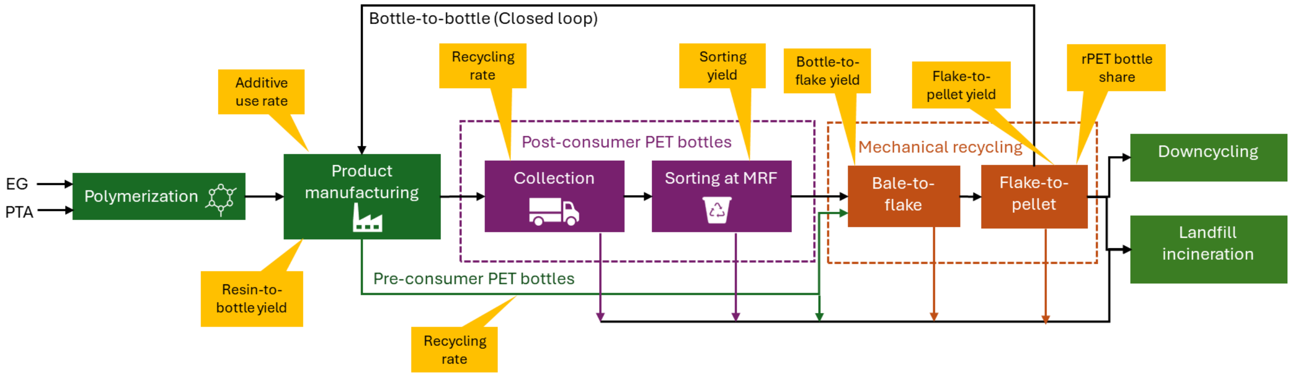

Figure 1. Supply chain of PET bottles with mechanical recycling. EG: Ethylene glycol, TPA: Purified terephthalic acid, MRF: Material recovery facility, PET: Polyethylene terephthalate. (Adapted from Gracida-Alvarez et al.[5]).

As shown in Figure 1, the flows in PET production and recycling are governed by several parameters listed in Table 3, which reflect the state of PET bottle production and mechanical recycling in the United States in 2017—the basis for the data used in this study. In 2017, the annual production of PET bottles was estimated at 2680 kt.[1]

Table 3. Parameters used in the MFA estimations of PET bottles production and mechanical recycling process (adapted from Gracida et al, 2025).

Parameter	Baseline Value	Alternative*	Definition
Recycling rate[27]	29 %	75%	Fraction of discarded post- and pre-consumer PET bottles that are recycled
Sorting yield[28]	87 %	95%	Fraction of PET that is properly identified, sorted, and packed at material recovery facilities (MRFs)
Bottle-to-flake yield[29]	67 %	N/A	Percentage of input PET, from bales, that remains in flakes after the reclaiming process
Flake-to-pellet yield[30]	96 %	N/A	Percentage of PET input from flakes that remain in the recycled PET (rPET) pellets after mechanical extrusion
rPET bottle share[27]	21 %	70%	Fraction of rPET processed in bottle-to-bottle (closed-loop) recycling, which is converted back into bottles.
Resin-to-bottle yield[24]	91 %	N/A	Percentage of input PET resin that remains in bottles

*"Alternative" refers to the scenario evaluated in Figure 3. N/A: non-applicable

Estimated mass fractions of PET bottle additives are shown in Table 4. This information was critical for determining the mass fractions that reflect as closely as possible industry practices; however, as this type of information is usually proprietary and not available for specific applications, we rely on literature[19,20,31,32] and discussion with experts from the plastics sector. In addition to earlier additive groups, PET bottles frequently include oxygen scavengers, acetaldehyde scavengers, and fast-reheat stabilizers. Table 4 provides mass-fraction ranges, using the average as the baseline and the low/high values as the corresponding minimum and maximum estimates.

Table 4. Mass fraction range of additive groups utilized in PET bottles[5]

Additive group	Additive chemical	% Mass fraction range Low to high (average)
Pigment	Titanium dioxide	0.50 -1.60 (1.05)
Oxygen scavenger	Oxbar® (Nylon-based)	0.03- 2.00 (1.02)
Acetaldehyde scavenger	Anthranilamide (2-aminobenzamide)	0.03-0.12 (0.08)
UV stabilizer	Benzophenone	0.10-0.30 (0.20)

Fast reheat	Carbon black	0.005-0.01 (0.008)
Catalyst	Antimony trioxide	0.01-0.03 (0.02)

The reduction or removal of additives that pose environmental concerns has the potential to enhance plastic recycling, as plastics containing these additives are currently excluded from recycling streams and diverted to alternative end-of-life management methods.[2,3] However, it is crucial to ensure that such reductions do not compromise the thermochemical properties of the resin, which are essential for maintaining functionality. For certain plastic products with high concentrations of additives known to pose environmental risks, proper sorting and removal from collection streams are preferred over recycling.[2] As a result, some additives can impact the recyclability of plastics, and reducing their concentrations could be expected to improve recycling rates. Since no studies evaluating this outcome are currently available, input from industry experts was sought to obtain data and guidance. However, many key parameters remain highly uncertain due to limited information. As a result, an initial hypothetical assessment was conducted. This analysis serves as a step toward developing more efficient recycling processes that could increase the value of recycled materials.

In the absence of data, such as information that connects variations in PET additive mass fractions to recycling flows, this report introduces a conceptual sensitivity analysis with four scenarios: (1) a baseline reference estimate derived from data in Table 3; (2) a hypothetical scenario where reductions in additive mass fractions could increase the rPET bottle share; (3) a hypothetical scenario combining the same rPET share increase with an enhanced recycling rate facilitated by mechanisms such as deposit-refund schemes and recycling funds; and (4) a final hypothetical scenario where additionally sorting yields in MRFs are improved, also through the implementation of deposit-refund schemes, incentives in recycling programs, and improvements in sorting.[5] This scenario was not evaluated by Gracida-Alvarez et al.[4] and thus provides new insights to the analysis. The factors evaluated in the scenarios—recycling rate, rPET bottle share, and sorting yield—have been shown to be impacted by strategies aimed at increasing the circularity of plastics.[5,6] These factors also have a key influence on the material flows that define circularity and the environmental impacts of the plastic supply chain.[6] However, it is important to note that further evidence is required to establish their dependence on the reduction of additive concentration. For Scenario 2, it is assumed that the lower mass fraction of additive content (Table 4) will lead to higher quality resin, allowing the increase of the share of recycled PET (rPET) directly to closed-loop bottle-to-bottle application. Based on reported outcomes from recycling refund (deposit-return) mechanisms, we assume the share of recycled resin used in bottles rises from 21% to 70%.[30] Scenario 3 considers broader recycling initiatives and sets the PET bottle recycling rate at a hypothetical 75% from 29%, aligning with the highest documented rate in any state, associated with recycling refund schemes.[30] Although losses at MRFs can be reduced up to 12%,[30] Scenario 4 uses a sorting yield in MRFs is increased from 86.7% to 95% due to recycling refund schemes.

Results and Discussion

Table 5 and 6 provide a summary of the environmental metrics evaluated for selected additive chemicals commonly found in PVC and PET resin formulations. Most of these values were sourced from Gracida-Alvarez et al.[5], while for chemicals not covered in that study—such as titanium dioxide, nylon MXD6, carbon black, and antimony trioxide—data from patents[33-35] and other reports[36,37] were utilized to develop the LCIs and estimate the associated GHG emissions and fossil energy use. For anthranilamide, aniline was used as a proxy, with industrial database information employed to construct the LCI.[38] The analysis revealed that, among the representative chemicals chosen for each category, oxygen scavengers and flame retardants exhibited the highest GHG emissions and fossil energy consumption. This is primarily attributed to the use of chemicals such as bromine (for flame retardants) and m-xylylenediamine (for oxygen scavengers), with high GHG emissions and fossil energy use in their production. In contrast, additive groups like plasticizers, stabilizers, acetaldehyde scavengers, and catalysts reported GHG emissions below 3.5 kg CO_2e/kg. Similarly, flame retardants and oxygen scavengers showed the highest fossil energy use, driven by the energy-intensive extraction or synthesis of the compounds required for their production. The elevated energy demands for the processing of these compounds (i.e., bromine and m-xylylenediamine) significantly contribute to the overall fossil energy use of these additives.

Table 5. GHG emissions (kg CO_2e/kg), fossil energy use (MJ/kg) of flame retardants, plasticizers, pigments, and stabilizers.

Group	Flame retardants	Plasticizers	Pigments	Stabilizers

Chemical	TBBPA	DecaBDE	DINP	DEHP	Lead chromate	Chromium trioxide	Titanium dioxide	Barium nonylphenate	Benzophenone
GHG emissions	9.4	9.7	3.5	2.4	6.2	3.8	7.7	2.2	3.1
Fossil energy use	159	165	85	77	92	52	98	119	82

Note: TBBPA: Tetrabromobisphenol-A, decaBDE: Decabromodiphenyl ether, DINP: Di-isononyl phthalate, DEHO: Di-2-ethylhexyl phthalate.

Table 6. GHG emissions (kg CO_2e/kg), fossil energy use (MJ/kg) of oxygen and acetaldehyde scavenger, fast reheat additive, and catalyst used in PET bottles.

Group	**Oxygen scavenger**	**Acetaldehyde scavenger**	**Fast reheat**	**Catalyst**
Chemical	Nylon MXD6	Anthranilamide	Carbon black	Antimony trioxide
GHG emissions	21.0	2.4	2.3	0.1
Fossil energy use	437	83	57	1

The results of the analysis for PVC and PET resins formulated for various products are presented in Figure 2. For PVC, the low impact utilizes the chemical within each category with the lowest GHG emissions (DEHP, decaBDE, chromium trioxide, and barium nonylphenate), while the high impact employs the chemical with the highest GHG emissions (DINP, TBBPA, lead chromate, and benzophenone), as detailed in Table 5. In the case of PET, since only one representative chemical is selected for each additive group, the low and high impacts categories use the corresponding lowest and highest mass fractions provided in Table 4. As anticipated, the inclusion of additives leads to an increase in GHG emissions and fossil energy use for the formulated resins. For PVC, GHG emissions can rise by as much as 25%, as observed in insulation applications, or by as little as 0.3%, as seen in sewer pipes. In the case of PET bottles, the emissions of formulated PET resins range from 2% to 34%. Regarding fossil energy use, formulated PVC resins show increases between 28% and 35%, while PET bottle resins exhibit fossil energy increases ranging from 1% to 14%. The breakdown of GHG emissions and fossil energy use indicates that, for PVC, plasticizers are the largest contributors to these impacts in resin formulations. Although plasticizers do not have the highest GHG emissions per kg among the additives evaluated, their high mass fraction, as indicated in Table 1, makes them the most impactful additives. Conversely, flame retardants, despite having the highest GHG emissions and fossil energy per kilogram, contribute less significantly due to their low mass fraction in PVC formulations. Therefore, for PVC products, the environmental impacts are primarily driven by the mass fraction of the additive rather than the emissions or energy use associated with the additive itself. For PET resins, oxygen scavengers emerge as the most influential additive in terms of GHG emissions and fossil energy use. A comparison of high and low scenarios reveals that increasing the concentration of nylon MXD6 from 0.03% to 2% can elevate the GHG emissions of PET resin by 30%. This highlights that, for formulated PET resins used in bottles, the concentration of additives plays a significant role in determining the environmental impacts of the resin. Figure 2 indicates that additives have an insignificant impact in the low-case scenario; however, they warrant consideration only in the high-case scenario.

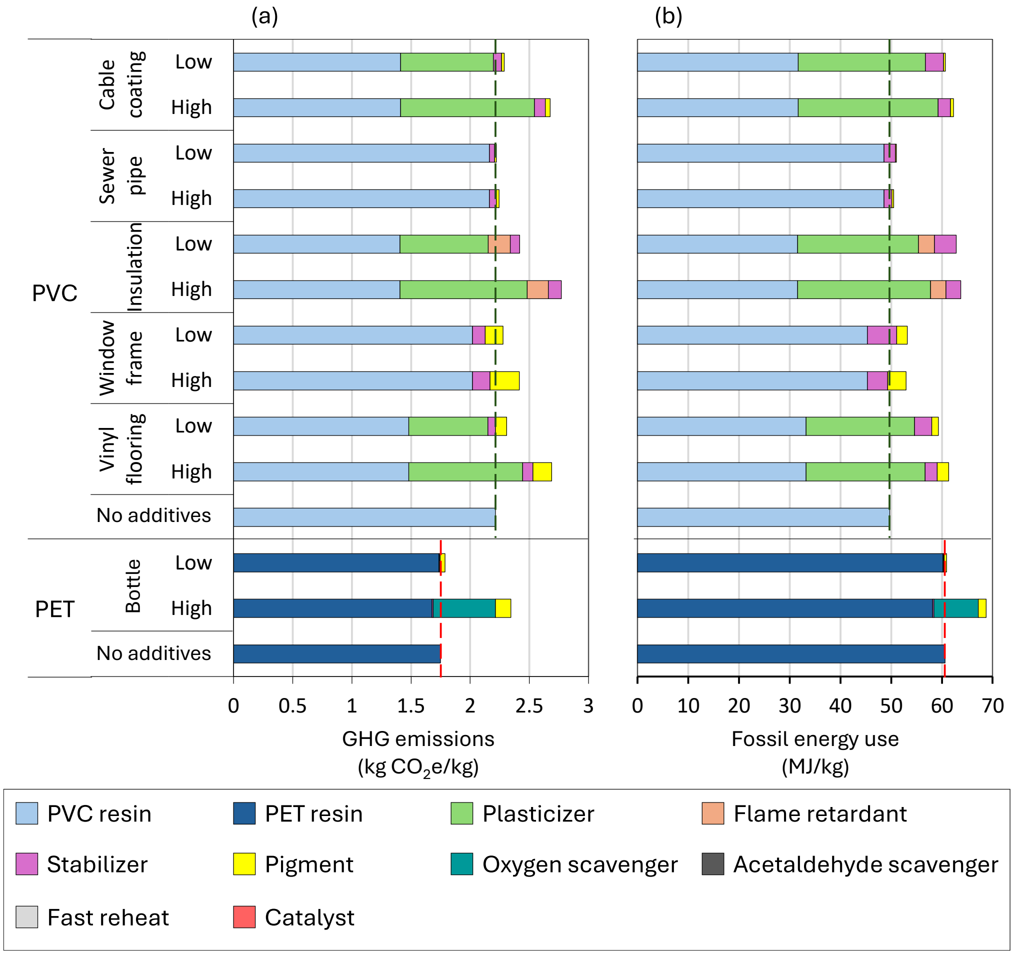

Figure 2. (a) GHG emissions and (b) fossil energy use of additives PVC and PET resins formulated with additives for different products. Dashed lines indicate the impact for PVC (green) and PET (red) without additives.

The Sankey diagrams generated from the MFA of the baseline and hypothetical scenarios are presented in Figure 3. The baseline scenario, representing the PET supply chain in 2017, estimates that 2,444 kt of PET are sent to EOL, while only 0.1 kt of rPET are reintegrated into the production of PET resins, resulting in a recycled content of 3%. Scenario 2 (Figure 3b) demonstrates that increasing the rPET bottle share from 21% to 70% raises the rPET content in formulated PET resin to 12% and reduces virgin material use by 7%. Scenario 3 incorporates both the effects of increasing the rPET bottle share and the recycling rate of PET bottles, achieving an rPET content of 30% in formulated PET resin, along with reductions in virgin material use and PET sent to EOL by 26% and 31%, respectively, compared to the baseline scenario. Scenario 4 incorporates an improvement in the sorting yield of PET bottles at material recovery facilities (MRFs) from 86.7% to 95% in addition to the assumption of Scenario 3. As shown in Figure 3d, this scenario increases the rPET content in formulated PET resin to 32%, while reducing virgin material use and solid waste generation by 29% and 36%, respectively, compared to the baseline scenario. Among the four scenarios analyzed, Scenario 4 achieves the highest rPET content and the lowest virgin material use and solid waste generation. Notably, the most significant increase in rPET content in formulated resin, compared to the baseline, occurs when the recycling rate is raised from 29% to 75% in Scenario 3. Similarly, the largest reductions in virgin material use and solid waste generation are observed in the transition from Scenario 2 to Scenario 3. This underscores the critical role that increasing the recycling rate plays in enhancing the use of recycled material within the PET bottle supply chain.

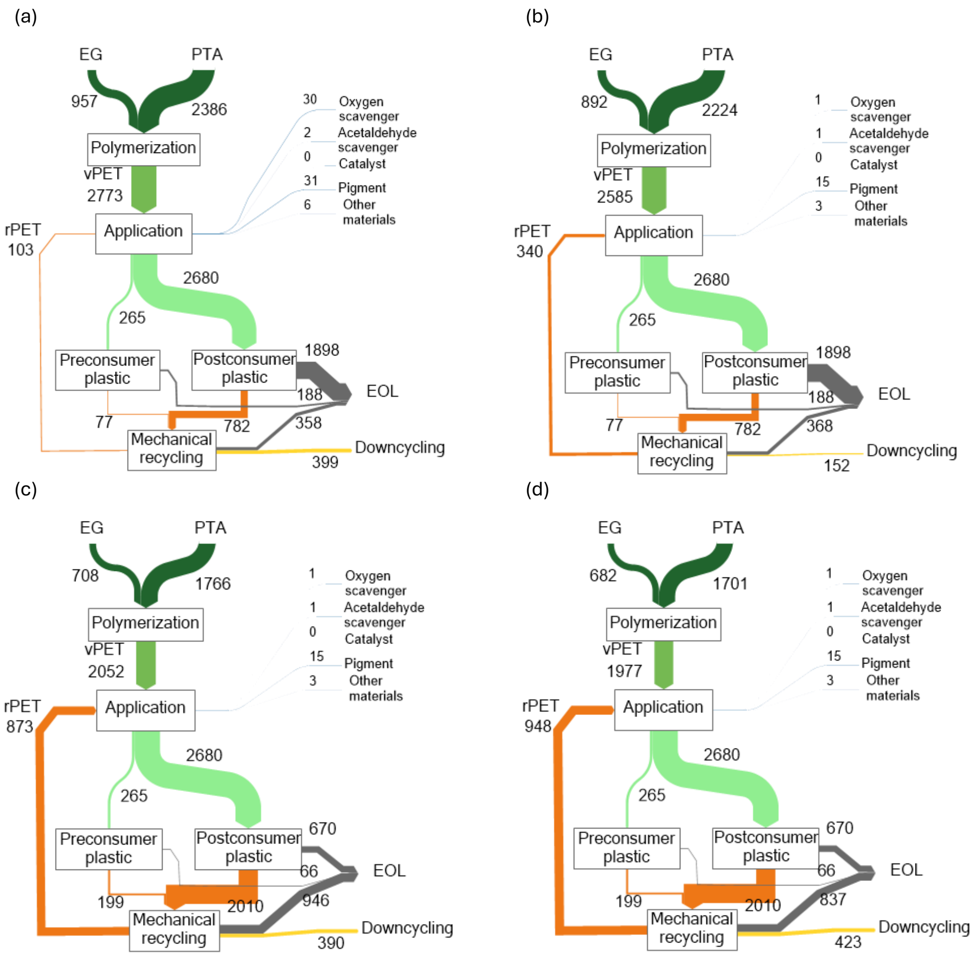

Figure 3. Sankey diagrams scenarios evaluated. (a) baseline (Scenario 1), (b) increment of the rPET bottle share to 70% (Scenario 2), (3) increment of rPET bottle share to 70% and recycling rate to 75% (Scenario 3) and (4) increment of rPET bottle share to 70%, increment of recycling rate to 75%, and increment of the sorting yield of PET at MRFs to 95% (Scenario 4).

Figure 4 illustrates the variations in virgin material use, solid waste generation, and GHG emissions resulting from the independent adjustment of three material flow factors analyzed in this study: rPET bottle share, recycling rate, and PET sorting yield at material recovery facilities (MRFs), using a functional unit of one kilogram of PET bottles. The results indicate that virgin material use and GHG emissions are significantly influenced by the combined effect of variations in rPET bottle share and recycling rate. Notably, reductions in virgin material use and GHG emissions are more pronounced along different rPET bottle shares when the recycling rate increases to 75%. Independent increases in rPET bottle share and recycling rate lead to reductions in virgin material use of 8% and 6%, respectively, compared to the baseline, and reductions in GHG emissions of 4% and 2%, respectively. However, the combined effect of increasing both factors results in a substantial reduction in virgin material use and GHG emissions by 27% and 11%, respectively. In contrast, varying only the sorting yield at MRFs produces negligible reductions in virgin material use and GHG emissions compared to the baseline. These findings suggest that rPET bottle share and recycling rate are the two most impactful factors for reducing virgin material use and GHG emissions in formulated PET resins. As shown in Figure 4b, solid waste generation exhibits minimal variation with changes in rPET bottle share and sorting yield at MRFs. However, a significant decrease of 32% in solid waste generation is observed when the recycling rate increases from 29% to 75%. This reduction is primarily attributed to the fact that the majority of solid waste is generated during the collection of post-consumer and pre-consumer plastic, with only minor contributions from the recycling stages involving rPET bottle share and sorting yield at MRFs, as illustrated in Figures 3a and 3b.

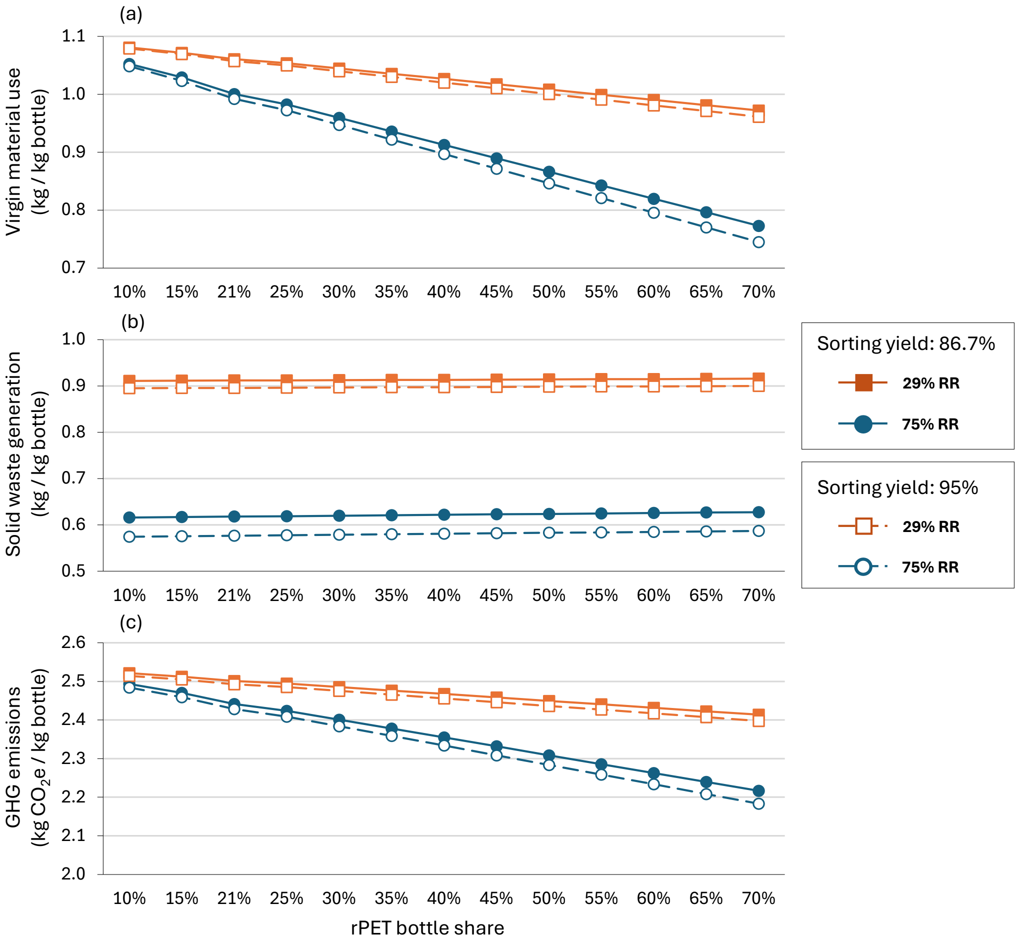

Figure 4. (a) Virgin material use, (b) solid waste generation, and (c) GHG emissions at different values of the material flow factors evaluated in this study. RR: Recycling rate.

Conclusions & Recommendations

The findings of this study reveal variability in the GHG emissions and fossil energy use associated with different additive groups used in the production of plastic products. Based on the chemicals selected for this analysis, flame retardants and oxygen scavengers emerged as the additive categories with the highest GHG emissions among all those evaluated. The analysis of GHG emissions and fossil energy use for formulated resins indicated that plasticizers and oxygen scavengers have the most significant impact on the environmental performance of PVC and PET resins, respectively. For PVC, plasticizers contributed to up to a 25% increase in GHG emissions and a 28% increase in fossil energy use, while for PET, oxygen scavengers resulted in up to a 34% increase in GHG emissions and a 14% increase in fossil energy use, compared to formulations without additives.

The supply chain analysis of PET bottles demonstrated that virgin material use and GHG emissions experienced the greatest reductions compared to the baseline scenario due to the combined effect of increases in rPET bottle share and recycling rate. In contrast, improvements in the sorting yield of PET at MRFs had a minimal impact on these metrics. Solid waste generation, on the other hand, was primarily reduced by increases in the recycling rate, with lesser contributions from changes in the other two factors evaluated.

It is important to note that major uncertainties in this study stem from variations in material flow factors due to reductions in additive concentrations, as no data is currently available to quantify these effects. The values used were derived from strategies aimed at increasing closed-loop recycling, which may not accurately reflect the impact of additive concentration reductions. Another source of uncertainty lies in the selection of material flow factors. While industry experts were consulted to identify parameters likely to be affected, actual evaluations may reveal additional or different factors influenced by additive reductions. Furthermore, some industry experts suggested that reducing additive concentrations could impact the functionality of plastic products, potentially shortening their use-phase lifespan. Such variations in material flows from the hypothetical scenarios could impact the outcomes of the study.

This study also highlighted the limited availability of data regarding the environmental impacts of additives and their mass fractions in different PET resin product formulations. For future work, we recommend expanding data availability in these areas, as it is important for understanding how additive concentrations affect recyclability and the environmental impacts across a broad range of plastic resins and investigating the potential accumulation of additives through successive recycling cycles to better understand their impacts on material quality and recycling efficiency in mechanical recycling processes.

Although significant advances are still required in this area, the insights from this preliminary work can help raise awareness in the plastic manufacturing community and provide valuable insights to optimize plastic product formulations. This approach ensures that additives are considered not only for their functional properties but also for their impact on product recyclability. For instance, during the additive selection and substitution steps (screening at formulation stage), this study provides a structured framework to identify "high-leverage" additive groups (plasticizers, flame retardants, pigments, stabilizers) that tend to dominate environmental impacts due to their prevalence, hazard profiles, and/or use levels. Manufacturers can use this framework as an early-stage screening tool to prioritize (i) avoiding certain chemistries, (ii) substituting to lower-impact alternatives within the same functional class, or (iii) reducing additive loading while maintaining product performance. On the other hand, the conceptual PET framework highlights that material-flow factors (sorting yield, contamination, closed-loop share) strongly influence recycled content and system-wide emissions. Manufacturers can apply this logic to avoid additives that affect sorting, melt stability, color quality, or reprocessing performance, and to select formulations compatible with high-yield mechanical recycling. This approach would enable the creation of plastic products that are recyclable by design while maintaining the desired properties for their intended applications.

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