DOI: 10.1111/jiec.13411

RESEARCH ARTICLE

JOURNAL OF INDUSTRIAL ECOLOGY WILEY

The environmental performance of plastic packaging waste management in Germany

Current and future key factors

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Editor Managing Review: Ichiro Daigo

Abstract

Plastic is a popular packaging material, but also criticized as a symbol for the make-use-dispose economy because of its short lifespan, its dependency on fossil fuels, and its potential contribution to marine litter. To identify current and potential future key factors for the environmental performance of plastic packaging waste (PPW) management in Germany, a life cycle assessment considering five different pathways of PPW (including deposit-refund systems, separately collected lightweight packaging waste, and treatment of non-source-separated residual waste) was performed. The analysis related to the year 2017 and also considered prospective changes in the background system until 2050 by adapting inventories to shared socioeconomic pathways in line with the Paris Agreement. Key factors for the environmental performance were determined by perturbation analysis. Source separation, quality and quantity of recycled plastics, and emissions from the thermal utilization of residues were identified as key factors for the environmental performance of PPW management. While benefits of PPW management are expected to decrease due to prospective system changes, source separation and the separation of plastics from residual waste gain in importance. Potential measures for improving the environmental performance should focus on long-term key factors, especially separating PPW from the residual waste (in households or in waste treatment facilities) as well as increasing the quantities and qualities of recycled plastics. The present study showed that the evaluation of system performance in view of changing boundary conditions is key to identify optimal configurations of future PPW management.

KEYWORDS
industrial ecology, integrated assessment models, perturbation analysis, plastic packaging waste, prospective life cycle assessment, waste management

1 INTRODUCTION

In previous decades, plastic became a popular packaging material due to its low inherent weight, low costs, good processability, and customizable features (Andrady & Neal, 2009). Plastic packaging protects food against spoiling and prevents mechanical damage of packaged goods (White & Lockyer, 2020) and is often accountable for only a small proportion of environmental impacts, compared to the impacts of the packaged product (Kan & Miller, 2022). As the usage of plastic packaging prevailed, plastic packaging waste (PPW) quantities increased. From 1991 to 2010, the PPW quantities generated in private households in Germany doubled (Burger et al., 2021). Since 2015, PPW quantities in Germany stabilized at around 25 kg per person and year (Burger et al., 2021). Nowadays, plastic packaging is often criticized as a symbol of the so-called make-use-dispose economy because of its short lifespan, its dependency on fossil fuels, and its potential contribution to marine litter (Xanthos & Walker, 2017).

As a reaction to the tension between functionality and the short-term and linear product life, the European Union identified “Packaging” and “Plastics” as two of the key product value chains in the “New Circular Economy Action Plan” (European Union (EU), 2020). With a focus on packaging, the European Directive on Packaging and Packaging Waste provides measures to prevent or reduce impacts of packaging and packaging waste management on the environment (EU, 2018). It obliges the member states to provide return, collection, and recovery systems for used packaging and packaging waste.

In Germany, PPW collection is carried out via deposit-refund-systems (DRSs) for reusable and single-use beverage packaging and a source-separation scheme for recyclable materials from private households. The current level of PPW recovery and recycling in Germany has been assessed from a material perspective by previous studies (Picuno et al., 2021; Schmidt & Laner, 2021), but a recent evaluation of the environmental performance of plastic packaging waste management (PPWM) in Germany is missing. Existing studies are outdated (Wollny et al., 2002) or focus only on specific parts of PPWM in Germany (Bulach et al., 2022; Dehoust et al., 2016; Volk et al., 2021). Dehoust et al. (2016) showed that increasing sorting and recycling efficiencies of lightweight packaging waste (LPW) treatment is associated with increasing environmental benefits in terms of global warming, acidification, and cumulative energy demand, but decreasing environmental benefits in terms of eutrophication. Similar trade-offs between impact categories (ICs) were also observed for plastic packaging waste management systems (PPWMSs) in other regions (Ferreira et al., 2014; Civancik-Uslu et al., 2021; Rigamonti et al., 2014; Van Eygen et al., 2018). It was found that improving the efficiency of municipal solid waste incineration (MSWI; Haupt et al., 2018) or putting a focus on high-quality products from recycling (Van Eygen et al., 2018) are effective measures for reducing climate change impacts from PPWM. While the studies by Rigamonti et al. (2014), Van Eygen et al. (2018), Ferreira et al. (2014), Haupt et al. (2018), and Schmidt et al. (2020) are retrospective analyses, the future environmental performance of PPWM has not been analyzed in view of anticipated changes in energy and material systems. In a waste management context, prospective life cycle assessments (LCAs) were mainly performed to assess the environmental performance of emerging treatment technologies (Civancik-Uslu et al., 2021; Bisinella et al., 2021; Volk et al., 2021) or future waste management scenarios (Meylan et al., 2014, 2018; Münster et al., 2013). So far, the consideration of prospective system transformations in waste LCAs has been restricted to simplified scenarios (Bisinella et al., 2021; Moora &Lahtvee, 2009; Zhao et al., 2022), although methods to consider prospective developments in LCA background databases have been developed (Beltran et al., 2018; Sacchi et al., 2022). The aim of this study is to assess the current and potential future environmental performance of PPWM in Germany in consideration of prospective changes in the background system and to identify key factors for the environmental performance of PPWM as a basis for future optimization.

2 METHODS

2.1 Life cycle assessment

LCA is a standardized method for quantifying environmental impacts, health impacts, and resource depletion issues associated with the whole life cycle of a good or a service (JRC, 2011a). In this study, LCA calculations were performed using the Python-based open-source framework Brightway2 (Mutel, 2017) because Brightway2 enables flexibility in terms of LCA modeling and analysis of LCA results, for example, by combining Brightway2 with other Python packages (e.g., packages for extensive scenario analysis (“presamples,” Lesage et al., 2018)). LCA consists of four steps, namely, goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation (DIN EN ISO 14040, 2006a; DIN EN ISO 14044, 2006b).

The goal of the LCA is to assess environmental impacts, health impacts, and resource depletion issues related to the treatment of PPW collected in Germany in 2017. Respectively, the functional unit is defined as the amount of PPW collected in Germany in 2017 considering five pathways for PPW (Figure 1): PPW collected within the DRS for reusable PET bottles (P1) is prepared for reuse. Caps and rejects from the preparation for reuse process are directed to recycling. Separately collected single-use PET bottles and their caps (P2) are also treated in recycling processes. PPW collected as part of LPW (P3) is sorted for subsequent recycling. Residues from sorting and recycling processes are incinerated in MSWI plants or used as a refuse-derived fuel in the cement industry. Plastic packaging in the residual waste is partly directed to MSWI (P4) and partly to mechanical–

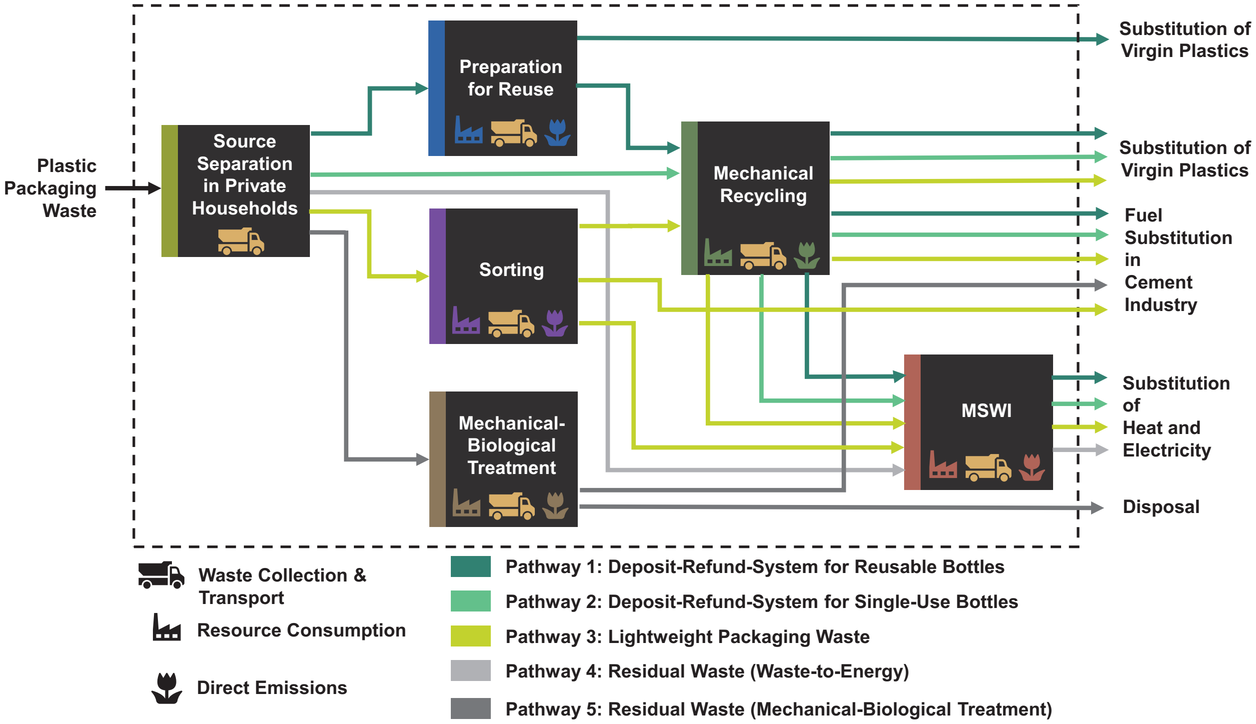


FIGURE 1 Schematic illustration of the treatment of PPW in Germany 2017.

biological treatment (MBT, P5). Residues of MBT processes are used as a refuse-derived fuel or landfilled. For a detailed documentation of the model structure see Section 1 of Supporting Information S1.

LCI data are taken from several studies (Dehoust et al., 2016; Doka, 2003; Juhrich, 2016; Koehler et al., 2011; Nessi et al., 2012; Van Eygen et al., 2018) and statistics (BMU, 2018; BMWi, 2021; Statista, 2021; VDZ, 2021) or are extracted from the ecoinvent database (v3.7.1, cut-off system model, Wernet et al., 2016). Datasets on PPW treatment are adjusted to processes and flows in the material flow model on PPWM in Germany 2017 (based on Schmidt & Laner 2021, complemented by additional literature sources; Dehoust et al., 2016, Picuno et al., 2021a; and implemented in ODYM [Python-based open-source software library for material flow analysis, MFA; cf. Pauliuk & Heeren, 2020] to consider multiple model aspects (time, material, pathway, Monte Carlo run) and to allow for a smooth interface between MFA and LCA calculations (cf. Section 1 in Supporting Information S1). The model is established for 2017 (time), six material layers (flexible plastic packaging [films], and the five rigid plastic types high-density polyethylene [PE-HD], polypropylene [PP], polyethylene terephthalate [PET], polystyrene [PS], and expanded polystyrene [EPS]) and the five most relevant pathways with regard to treated PPW quantities (DRS for reusable bottles, DRS for single-use bottles, LPW waste, thermal treatment of residual waste, and MBT of residual waste). Data uncertainty is accounted for via the pedigree approach (Weidema et al., 2013) under the assumption of lognormal distributed values. The PPW is considered to be burden free ("zero burden assumption," cf. Nakatani, 2014). All other inputs to the PPWMS (energy, fuel, materials, etc.) are accounted for. Co-production due to recycling and energy recovery is considered via system expansion (subtractive approach, cf. JRC, 2011a). For all co-products, functionally equivalent products are identified representing the average products for the given region and time (attributional modeling principle, cf. JRC, 2011a). Mass-based mono-material substitution factors are used for avoided materials, whereas substitution factors for avoided fuels and energy are calculated based on calorific values under the assumption of energy equivalence. Detailed information on the LCI and assigned data uncertainties can be found in Supporting Information S1 Section 2.1 and in S2.2 in the Zenodo archive. Applied substitution factors and avoided products are documented in Section 2.2 of Supporting Information S1.

As part of the LCIA, emissions and resources derived from the LCI are assigned to ICs. In this study, environmental impacts, health impacts, and resource depletion issues are quantified in 16 ICs (Global warming [GW], Ozone depletion [OD], Human toxicity—cancer effects [HTc], Human toxicity—non-cancer effects [HTnc], Particulate matter [PM], Ionizing radiation—human health [IR], Photochemical ozone formation [POF], Terrestrial acidification [TA], Terrestrial eutrophication [TE], Freshwater eutrophication [FE], Marine eutrophication [ME], Ecotoxicity [ET], Land use [LU], Resource depletion—water [RDw], Resource depletion—minerals and metals [RDm], and Resource depletion—fossil [(RDf]). The selected ICs and corresponding LCIA methods comply with the recommendation by JRC (2011). Calculated impacts in all ICs are converted into person equivalents (PE) using global normalization factors for emissions and resource extraction (Sala et al., 2017). Contribution analysis is carried out to identify activities dominating the environmental performance (Heijungs & Kleijn, 2001). The uncertainty of LCA results is assessed based on Monte Carlo simulation with 1000 runs (cf. Section 2.4 in Supporting Information S1).

2.2 | Perturbation analysis

Perturbation analysis serves to assess the influence of parameter changes on LCA scores (Clavreul et al., 2012). It is performed by reproducing LCA calculations for an incremental increase of each parameter individually ("one-at-a-time-approach"), while all other parameters remain unaffected (Bisinella et al., 2016; Clavreul et al., 2012). Perturbation analysis is implemented for 273 parameters in the foreground system considering an incremental increase of parameter values of 1% by adapting the inventory matrix to precalculated parameter changes (cf. S2.3 in the Zenodo archive) applying the Python package "presamples" (Lesage et al., 2018). Results of the perturbation analysis are evaluated by means of sensitivity ratios which are calculated as a ratio between relative changes of LCA results and relative changes of parameter values compared to the initial system (Bisinella et al., 2016; Clavreul et al., 2012). For example, a sensitivity ratio of 0.5 implies that an increase of the parameter value by 10% results in an increase of LCA scores by 5% (Clavreul et al., 2012). All resulting sensitivity ratios are given as absolute values (distance to 0) to simplify the joint interpretation of parameters with positive and negative default values (e.g., waste treatment exchanges, cf. Guinée & Heijungs, 2021). The parameters are classified into parameter categories describing the parameter's application in the LCA model.

2.3 | Prospective LCA

A prospective LCA is performed to identify potential future trends concerning the environmental performance of PPWM. For complying with the remaining CO_2 budgets according to the 1.5°C limit as part of the Paris Agreement, a rapid reduction of CO_2 emissions is needed (UN, 2015; IPCC, 2022). The actual design and implementation of respective changes in various industry sectors depends on political actions. To describe potential future socioeconomic development, the climate change research community established the use of integrated assessment models (IAM) in combination with shared socioeconomic pathways (SSP; Riahi et al., 2017) and representative concentration pathways (RCP). In this study, the output results of the IAMs REMIND v2.1 (Baumstark et al., 2021) and IMAGE v3.2 (Stehfest et al., 2014) under consideration of a limitation of global warming to 1.5°C (REMIND SSP2-PkBudg900; IMAGE SSP2-RCP19) are used. The IAM output results are implemented in the LCA model by means of the Python-based software package "premise" (Sacchi et al., 2022) which allows for modifying the ecoinvent 3 cut-off database in accordance with output results of IAMs by adding additional inventories in the categories electricity generation, steel and cement production, liquid and gaseous fuels production and transport, and by modifying process efficiencies and markets to reflect the anticipated material and energy system at a certain point in time. In addition, manually created background system processes (market for heat; substitution of fuels in cement industry) are adapted based on recent studies (Gerhardt et al., 2021; Sacchi et al., 2022; cf. Section 2.3 in Supporting Information S1) in line with the aforementioned output results of the IAMs. These manual adaptations were necessary because adaptations predefined in "premise" target only datasets of the original ecoinvent database. The adapted LCIs are used to calculate LCA scores and sensitivity ratios for the years 2025, 2030, 2040, 2045, and 2050 to identify potential trends regarding the future development of the environmental performance of PPWM and its key factors.

3 | RESULTS

3.1 | PPW flows in Germany

In Germany 2017, 2554 kt of PPW was collected from private households. The PPW consisted of 791 kt films, 1236 kt PET, 303 kt PP, 201 kt PE-HD, 12 kt PS, and 12 kt EPS. Within the DRS, 520 kt of reusable PET bottles and 56 kt caps were returned to collection points (P1, cf. Figure 2). Ninety–six percent of the returned reusable PET bottles were reused. The remaining PET bottles (21 kt) and the caps made of PE-HD and PP (56 kt) were directed to mechanical recycling resulting in 63 kt of recycled plastics. Residues of the recycling process (13 kt) were used to substitute conventional fuels in cement kilns (98%) or utilized as energy in MSWI (2%). In the DRS for single-use PET bottles (P2) 436 kt of PET bottle waste were collected and directed to mechanical recycling resulting in a recycling rate of 90%. Residues of the recycling process were treated in cement kilns (98%) or in MSWI (2%). The collected LPW (983 kt, P3) was pretreated in sorting processes. The outputs of these sorting processes were various mono- and mixed polymer fractions for further treatment in mechanical recycling processes generating 463 kt recycled plastics. Sorting and recycling residues were used as energy (sorting residues: 78% in cement kilns, 22% in MSWI, recycling residues: 98% in cement kilns, 2% in MSWI). 559 kt of PPW from private households was collected in the residual waste due to a lack of source separation. Residual waste was either utilized as energy in MSWI (83%, P4) or processed in MBT (17%, P5). In terms of PPW, MBT aimed to separate the plastics to a high-calorific output fraction for further treatment as a refuse-derived fuel in cement kilns. However, small quantities of PPW (6 kt) remained in the output fraction for disposal. Overall, PPWM resulted in a recycling rate of 45%.

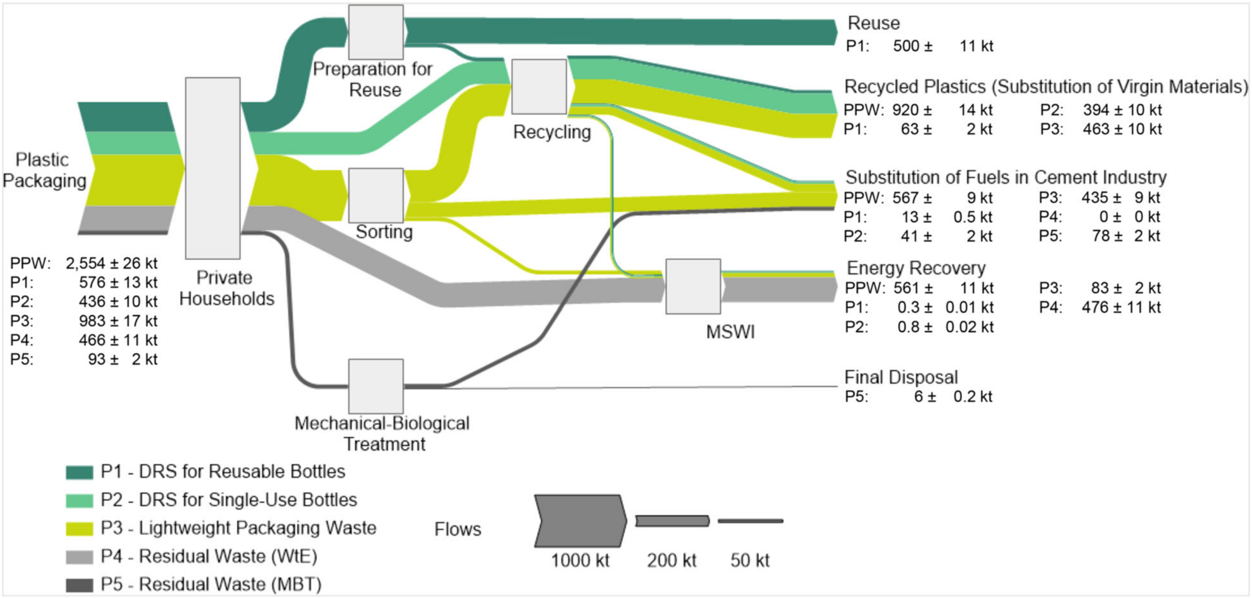


FIGURE 2 Flows (presented as mean values ± standard deviation) of PPW collected in private households in Germany 2017 displayed in Sankey style and subdivided by pathways. Underlying data can be found in S2.5 in the Zenodo archive at https://doi.org/10.5281/zenodo.7669434.

3.2 | Environmental performance of PPWM

The treatment of PPW from private households in Germany led to net environmental benefits in all ICs considered (cf. Figure 3). The largest net benefits were observed in the ICs RDm, HTc, and RDf followed by HTnc, OD, and GW with net benefits >4.5e5 PE. The main contributor to environmental benefits on pathway level was the DRS for reusable bottles (P1, cf. Figure 3a). Depending on the IC, the DRS for single-use bottles (P2) and the LPW (P3) also contributed substantially to environmental benefits. In the ICs GW and RDw, the environmental burdens of residual waste treatment by waste-to-energy processes (mainly emissions of the MSWI) outweigh the benefits of heat and electricity substitution, resulting in net environmental burdens of P4. The contribution analysis at process level (cf. Figure 3b) reveals that the largest environmental benefits were caused by credits for the avoided production of virgin materials. In addition, waste-to-energy and the substitution of fuels in cement kilns contributed to environmental benefits due to the avoided production of fossil fuels and heat and electricity. The burdens of the mechanical processing of PPW in sorting and recycling processes are comparatively small in most of the ICs. The impacts in the IC HTc constitute an exception due to the burdens of sorting and recycling. The contribution analysis at process level highlights also that waste collection and transport play only a minor role in all ICs under consideration.

3.3 | Perturbation analysis

A perturbation analysis was performed to identify key factors for the environmental performance of PPWM. In total, the sensitivity ratios of 273 foreground system parameters were calculated for each of the 16 ICs considered (cf. S2.7 in the Zenodo archive). In terms of GW, 13 parameters show sensitivity ratios above 10% (less than 1% of the parameters, cf. Figure 4b). These parameters belong to the categories "Source Separation," "Recycling," "Waste Management," "MSWI," and "Preparation for Reuse" (cf. colored markers in Figure 4a). The results are sensitive to changes of source-separation parameters (#1, #2, cf. labels in Figure 4a), because mis-sorted PPW collected via residual waste (#1) is not available for mechanical recycling and consequentially substitutes no virgin materials. The distribution of separately collected waste to DRSs (P1 and P2) and LPW (P3) (#2) is a sensitive parameter because benefits of PPW treatment via DRSs exceed benefits of LPW by factor 2.2 (P2) to 3.5 (P1). Besides source-separation parameters, treatment efficiencies and substitution factors show high sensitivity ratios. This concerns treatment efficiencies and substitution factors of PET (#3, #4, #7) and films (#11) due to their mass relevance. Other sensitive parameters in P3 are the distribution of sorting and recycling residues to MSWI or cement industry (#10, #12) because the substitution of fuels in the cement industry results in benefits whereas the incineration in MSWI plants is associated with burdens. Other waste management parameters decisive for the GW impacts of PPWM in Germany are the share of PET bottles in the DRS for single-use or reuse (#8) and the distribution of residual waste to MSWI or MBT (#5). In terms of MSWI, the CO_2 emissions (#6, #9; driven by the fossil carbon content in incineration inputs or downstream flue gas cleaning, such as carbon capture and storage [CCS]) are the MSWI parameters with the highest sensitivity ratios in the IC GW. Considering all 16 ICs, 24 parameters show

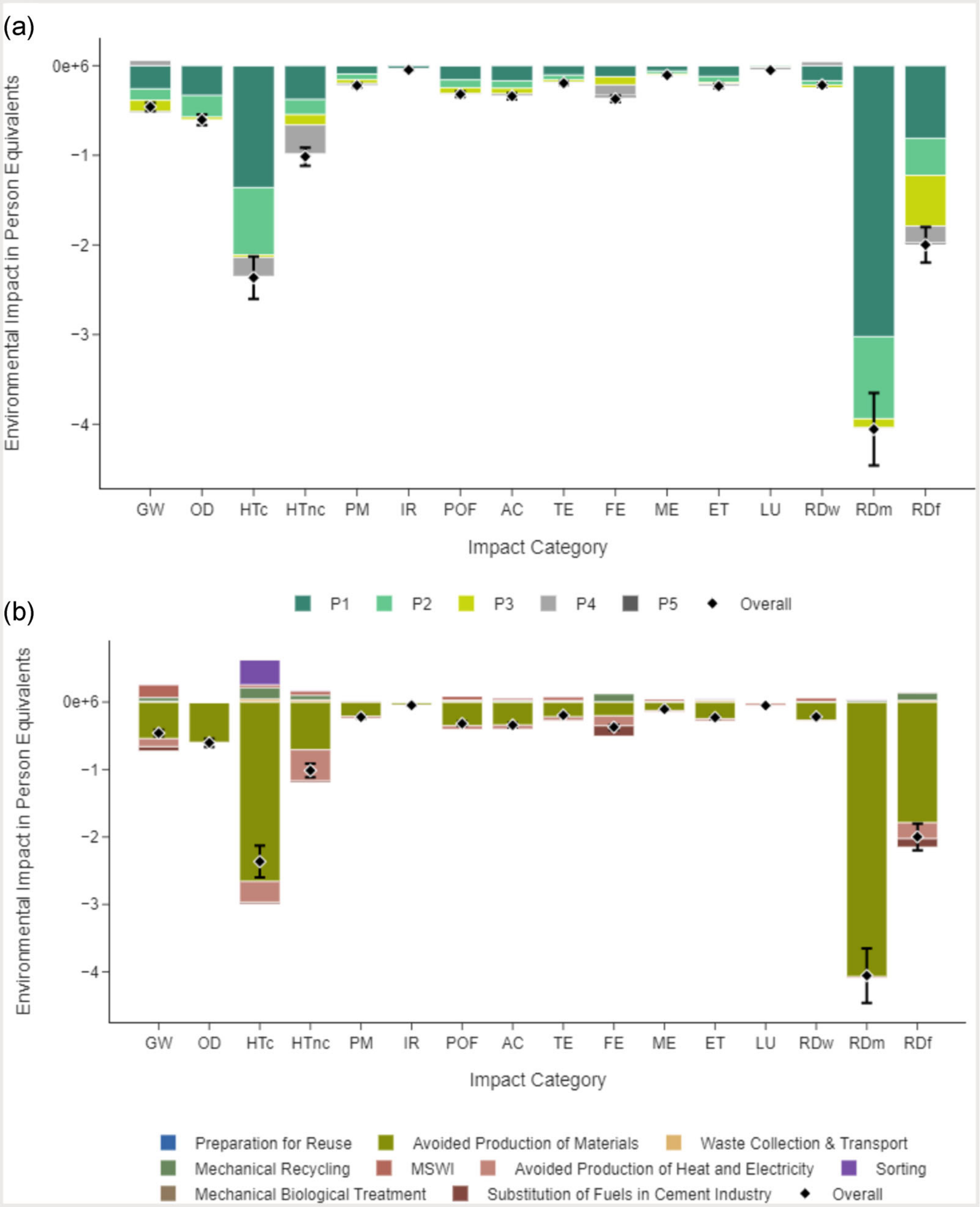
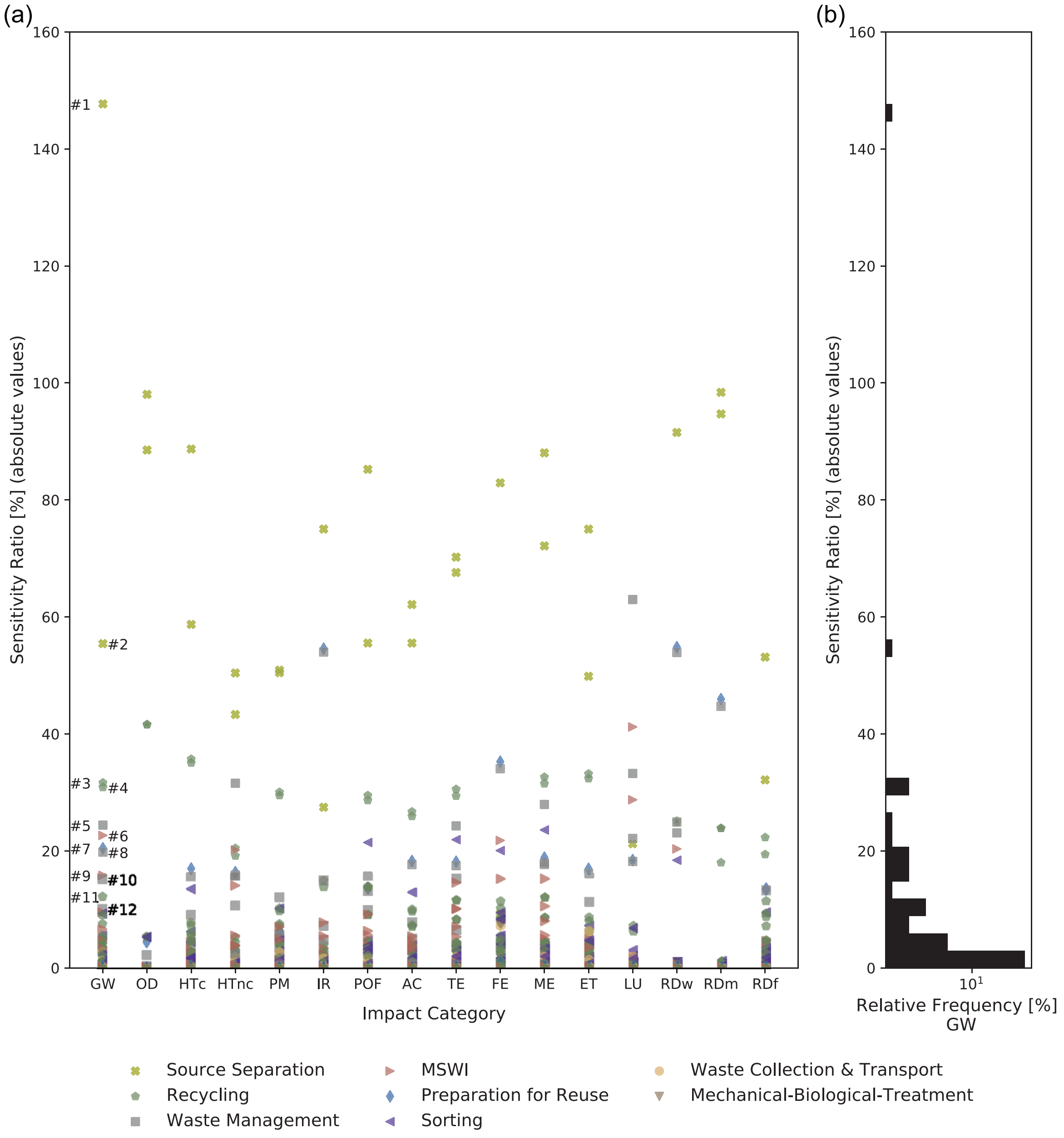


FIGURE 3 Environmental impacts of the PPWM in Germany 2017: a) Results on pathway level; b) Results on process level (functional unit: treatment of 2554 kt PPW), error bars display the standard deviation of results determined based on Monte Carlo simulations. Underlying data can be found in S2.6 in the Zenodo archive at https://doi.org/10.5281/zenodo.7669434.

sensitivity ratios above 10%. Thereof, 16 parameters are relevant in more than one IC. The only parameter with a sensitivity ratio above 10% in all ICs is the share of mis-sorted PPW (#1). The results of the perturbation analysis highlight that LCA scores mainly depend on a small selection of parameters, which can be understood as key factors for the environmental performance of PPWM in Germany.

3.4 | Prospective LCA

In terms of GW, PPWM in Germany continues to result in benefits through 2050 based on both IAMs (cf. Figure 3a), but a sharp decrease of benefits is expected (IMAGE: −74%, REMIND: −64%) mainly due to decreasing credits for heat, electricity, fuel, and plastic substitution. The decrease of environmental benefits of PPWM occurs mainly until 2030 and the impacts level off in the years 2030 to 2050 as remaining carbon budgets require a rapid transformation of the socioeconomic system in Germany (cf. First Act Amending the Federal Climate Protection Act; German Bundestag,



#1 – Distribution of PPW to treatment paths of separate collection (P1, P2, P3) or to residual waste (P4, P5) [Source Separation]
#2 – Distribution of PPW to DRSs or LPW [Source Separation]
#3 – Substitution factor for recycled plastics in food-grade quality made from PET bottles [Recycling]
#4 – Recycling efficiency of the PET bottle-to-bottle recycling process [Recycling]
#5 – Distribution of residual waste to MSWI and MBT [Waste Management]
#6 – CO_2 emissions of MSWI with dry air pollution control [MSWI]
#7 – Reuse efficiency of the preparation for reuse process for reusable bottles [Preparation for Reuse]
#8 – Distribution of PET bottles to P1 or P2 [Waste Management]
#9 – CO_2 emissions of MSWI with wet air pollution control [MSWI]
#10 – Distribution of sorting residues to cement kiln or MSWI [Waste Management]
#11 – Substitution factor for recycled plastics made from films [Recycling]
#12 – Distribution of recycling residues to cement kiln or MSWI [Waste Management]

FIGURE 4 Results of the perturbation analysis: (a) Sensitivity ratios of parameters in the foreground system classified into parameter categories; (b) Frequency distribution of sensitivity ratios in the IC GW. Underlying data can be found in S2.7 in the Zenodo archive at https://doi.org/10.5281/zenodo.7669434.

2021). In terms of IMAGE the transformation is modeled recursive dynamic (Sacchi et al., 2022) resulting in a peak in 2030 followed by a slight increase of benefits of PPWM, whereas the modeling principle of REMIND assumes perfect foresight (Sacchi et al., 2022) and results in a continuous decrease of environmental benefits. On pathway level, the largest changes in GW impacts occur in the pathways for residual waste. In P4 (MSWI of residual waste), environmental impacts increase by around 150% from 2017 to 2050 as a consequence of decreasing benefits for heat and electricity substitution. Also the environmental performance of residual waste treatment in MBT in P5 decreases. The calculations based on

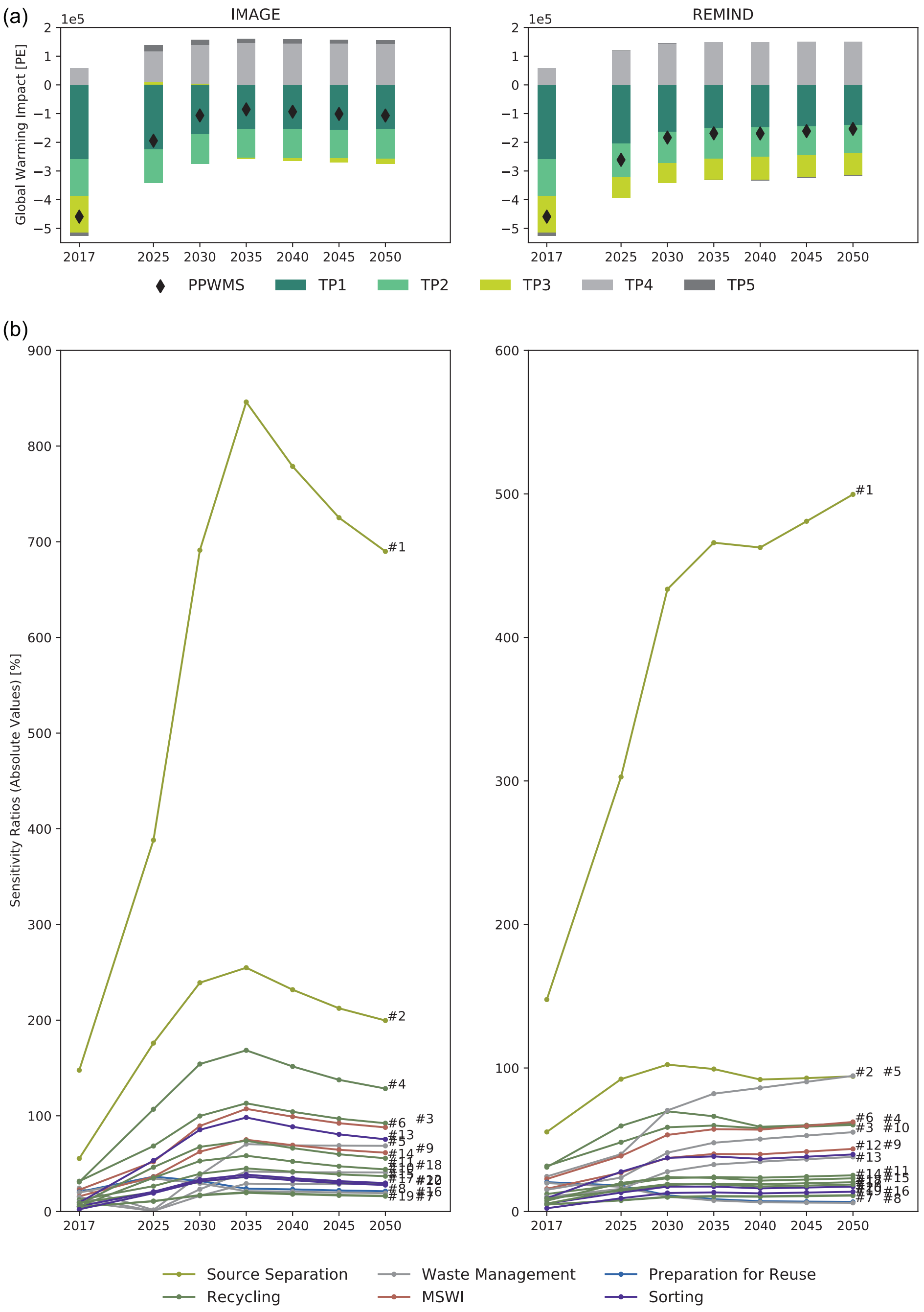
REMIND result in a decrease of benefits by 82%, whereas in case of IMAGE benefits turn into burdens. The effects in P5 are mainly caused by the transformations taking place in the cement industry, as 93% of PPW entering P5 ends up as a refuse-derived fuel. It is expected that in 2050 a less fossil carbon intensive fuel mix will be used and CCS technology will be partly implemented in cement industry (carbon capture rate: IMAGE: 55%, REMIND: 75%). A decreasing share of fossil fuels reduces the credits for fuel substitution, whereas introducing CCS is beneficial for the environmental performance of the combustion of conventional and alternative fuels. In case of REMIND, the changing fuel mix and the gradual implementation of CCS technologies results in burdens of P5 in the years 2025 and 2030, which are converted into benefits from 2035 on due to increasing carbon capture rates. A similar effect can be observed in terms of LPW treatment (P3), where the benefits decrease until 2050. In case of IMAGE, in the years 2025 and 2030 LPW treatment is associated with burdens caused by expected changes in the cement industry in combination with lower credits for the substitution of virgin plastics. However, the results based on both IAMs indicate that LPW treatment (P3) remains beneficial against residual waste treatment (P4 and P5) at any point in time. In terms of DRSs (P1 and P2), a reduction of GW benefits is expected based on both IAMs. The main drivers for decreasing benefits are reduced credits for the substitution of virgin plastics. Concerning key factors for the environmental performance of PPWM, the results of the perturbation analysis (cf. Figure 5b) show a raising number of parameters with absolute sensitivity ratios above 10% in the IC GW (2017: 12, 2050: 20). Most of the parameters with sensitivity ratios above 10% in 2017 gain importance based on the results of at least one of the IAMs considered. The sensitivity ratios of distributing PPW to pathways of the separate collection and pathways for residual waste (#1) more than triples from 2017 to 2050 due to increasing environmental impacts of residual waste treatment by P4. A strong increase of sensitivity ratios over time by factor three to eight is expected for the sorting and recycling efficiency of films (#13, #14) as well as the distribution of residual waste and sorting and recycling residues to subsequent treatment processes (#5, #10, #12) mainly because of the expected worsening of the environmental performance of MSWI. With respect to other ICs the trends differ depending on the IC and IAM, but the results in all 16 ICs have in common, that PPWM (assuming 2017 structures) is associated with environmental benefits with regard to background system changes until 2050 (cf. S2.6 and S2.7 in the Zenodo archive).

4 | DISCUSSION

4.1 | Key factors for the environmental performance of PPWM

The perturbation analysis revealed that source-separation parameters are decisive for the environmental performance of PPWM in all ICs (cf. Section 3.3). Source separation determines the type and quality of the subsequent waste treatment and enables substituting virgin materials and fossil fuels. In Germany in 2017, 78% of PPW was source separated (cf. Section 3.1). Comparing source-separation efficiencies for different plastic packaging products, plastic bottles as part of the DRS show higher source separation rates than other PPW (single-use and reusable bottles: 94%, other PPW: 64%). These positive features led to an expansion of the DRS to include also juice bottles in Germany in 2022 (German Packaging Law). However, the potential effects of this expansion are expected to be small, because juice bottles account only for around 46 kt of PPW (GVM, 2018) and the use of additives in these applications might affect the quality of recycled PET (Sängerlaub et al., 2020).

A large potential for improving the environmental performance of PPWM lies in the reduction of PPW collected via residual waste. In Germany, 559 kt of PPW are collected in the residual waste and are mainly used for energy recovery in MSWI or, to a minor degree, as refuse-derived fuel in cement kilns (cf. Section 3.1). Participation in source separation is influenced by a variety of factors, for example, consumption patterns and consumer behavior (Knickmeyer, 2020; Minelgaite & Liobikiene, 2019; Tong et al., 2018). An intensified use of material recovery facilities for residual waste is being discussed, particularly in urban areas with little participation in source separation, to exploit the resource potential in the residual waste (Lederer et al., 2022). In Germany, MBT is implemented as a low-intensity type of a material recovery facility, applied to 17% of residual waste (BMU, 2018), without separating plastics for recycling. In the Netherlands, material recovery facilities are used to produce two plastic concentrates (rigid and flexible) that can be recycled in mechanical recycling plants adjusted to higher impurity levels of input material (Picuno et al., 2021b). The large differences between the environmental performance of P4 and P5 indicate that residual waste splitting is environmentally preferable for PPWM compared to direct residual waste incineration regardless of the further utilization (material or energetic) of the separated plastic fraction. So far, the environmental performances of P4 and P5 mainly depend on the share of fossil fuels in energy mixes and the fossil CO_2 emissions of combustion processes as can be seen by the results of the perturbation analysis (cf. Section 3.3) and the prospective LCA (cf. Section 3.4). In general, benefits from MSWI will be higher for PPWM in countries with a more fossil-based energy system, whereas benefits will be reduced when the share of renewables increases. An option to reverse the trend of increasing net GW impacts of thermal treatment processes is the intensified implementation of technologies for reducing CO_2 emissions not only in the cement industry (as considered in Section 3.4) but also in MSWI. The effects of the implementation of CCS on the environmental performance of MSWI have been assessed by a few studies (Bisinella et al., 2021; Lausselet et al., 2017; Tang & You, 2018) showing environmental benefits in terms of GW, but worsening of environmental impacts in all other ICs. Apart from the latter, the storage of captured CO_2 is discussed as a critical factor for CCS (Lane et al., 2021). An alternative option for reducing the emissions of fossil CO_2 from MSWI is to reduce the content of fossil carbon in incineration inputs by intensifying the use of bio-based plastics in packaging applications. A comparison of the life cycle performance of bio-based plastic bottles made of polylactic acid (PLA) with petroleum-based alternatives



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#11 – Substitution factor for recycled plastics made from films [Recycling]
#12 – Distribution of recycling residues to cement kiln or MSWI [Waste Management]
#13 – Sorting efficiency for films in LPW [Sorting]
#14 – Recycling efficiency of the film recycling process [Recycling]
#15 – Substitution factor for recycled mixed plastics [Recycling]
#16 – Substitution factor for recycled PP [Recycling]
#17 – Sorting efficiency for PET in LPW [Sorting]
#18 – Recycling efficiency of the recycling process for mixed plastics [Recycling]
#19 – Recycling efficiency of the PP recycling process [Recycling]
#20 – Sorting efficiency for PP in LPW [Sorting]

FIGURE 5 Results of the prospective LCA: (a) Global warming impacts of PPWM (functional unit: treatment of 2554 kt PPW); (b) Sensitivity ratios calculated by means of perturbation analyses (parameters displayed show sensitivity ratios above 10% either in 2017 or in 2050 based on both IAMs). Underlying data can be found in S2.6 and S2.7 in the Zenodo archive at https://doi.org/10.5281/zenodo.7669434.

revealed benefits of the bio-based bottle in the ICs GW, OD, HTc, POF, AC, LU, and PM against the petroleum-based counterparts (Cappiello et al., 2022). However, disadvantages in the ICs FE, RDw, and TE (Cappiello et al., 2022) as well as the feedstock of bio-based materials that may compete with the production of crops for food (Weiss et al., 2012) are crucial aspects to be considered. At the moment, bio-based plastics play a subordinate role accounting for 0.3% of the global plastic production of 360 Mt in 2018 (Conversio, 2020).

Concerning the environmental performance of source-separated PPW treatment efficiencies were identified as sensitive parameters. Here, ambitious targets have been set on EU level for PPWM. By 2030 all plastic packaging placed on the EU market shall either be reusable or recyclable in an economically viable way (EU, 2020). To achieve this target measures on reinforcing design for reuse and recycling and reducing (over)packaging and packaging waste are under consideration. Also the waste treatment itself needs to be adapted to meet future recycling targets (2025: 50%; 2030: 55% as defined in the European Packaging Directive; EU, 2018). Besides source separation, sorting is the main origin of material losses within the PPWMS (cf. Section 3.1). Sorting technologies are refined resulting in a broader product portfolio and enabling new applications for recycled plastics (Dehoust et al., 2021). However, increasing treatment efficiencies may be associated with a quantity–quality trade-off (Van Eygen et al., 2018). To avoid a supply surplus due to a limited quality of recycled plastics and restricted application cases for recycled plastics, increasing secondary material quantities needs to go together with increasing qualities of recycled plastics (Klotz et al., 2022). Besides improving established technologies, implementing new technologies provides an opportunity for increasing resource efficiency and decreasing environmental impacts. Chemical recycling is discussed as an emerging treatment option for a significant fraction of the PPW stream. At this point, various chemical recycling technologies are under development (Solis & Silveira, 2020). The effect of implementing these technologies on environmental impacts of PPWM is widely discussed (Benavides et al., 2017; Civancik-Uslu et al., 2021; Meys et al., 2020; Möck et al., 2022; Volk et al., 2021). So far, comprehensive LCAs of chemical recycling technologies are missing due to a lack of data on operating plants and their operating conditions (Quicker et al., 2022).

4.2 | Limitations

The purpose of the LCA was to analyze the environmental performance of PPWM and to assess the effect of potential future transformations of the socioeconomic system on the environmental performance of PPWM (assuming current structure and technology) as a basis for optimizing PPWM in the future. Hence, inventory modifications are limited to processes in the background system of the LCA model and are solely based on the results of IAMs. Potential changes of the foreground system as a consequence of emerging waste treatment technologies are not considered, as IMAGE and REMIND do not cover transformations of plastics production or end-of-life treatment. In 2022, the model structure of the Plastics Integrated Assessment model (PLAIA, which is a sub-sub-sub-model of IMAGE) was published describing a first approach for considering trends in terms of plastic production and waste management in IAMs (Stegmann et al., 2022). PLAIA would allow for consideration of changes in plastic markets and recycled contents in plastic products or resource or emission reductions in plastic production in future studies, but model results have not been published yet. With regard to the prospective LCA results for PPWM in Germany, this would potentially lead to a further decrease of environmental benefits of PPWM, in particular regarding plastic recycling, because the credits for substituting virgin plastics would decrease.

In terms of modeling PPWM in Germany, simplifications had to be made including the pathways considered as well as chosen substitution factors and substituted products. Littering of plastic waste was not considered in the model, because less than 0.5% of the generated plastic waste are littered to the environment in Germany (BKV, 2020a, 2020b). The same applies for the disposal of PPW via biowaste, which accounts for 1% of PPW (Schmidt & Laner, 2021). Also not explicitly considered in the model is the export of PPW. According to Schüler (2019), in 2017 139–148 kt of PPW from LPW sorting outputs were exported. PPW exports and the treatment of this waste outside Germany were internalized in the model (assumed to be processed in Germany), because no data on the further treatment and utilization of the exported waste were available. Another model simplification was the representation of industrial combustion by use in the cement industry only, which neglects other industrial utilization options such as use in the steel industry. This assumption is motivated by less than 1% of PPW used as reductive agent in the steel industry in Germany (Conversio, 2018) and because it is in line with previous studies considering the industrial combustion of PPW (Bulach et al., 2022; Dehoust et al., 2016). Besides simplifications concerning the pathways considered, simplifications were made concerning the substitution, in terms of applied substitution factors and avoided products. In this study mass-based mono-material substitution is applied assuming that 1 kg of recycled plastics replaces 1 kg of virgin material. Alternatives to mass-based substitution factors are price-based or utility-based substitution factors. Depending on the market for crude oil, the demand for recycled plastics and their quality, price-based substitution factors are subject to permanent fluctuations (cf. Section 2.2.1 in Supporting Information S1). In case price-based substitution factors are applied, the environmental benefits of P3 in the IC GW decrease by 59%, meaning that the environmental performance of P3 falls below P5 (results for all pathways and ICs can be found in S2.8 in the Zenodo archive). Utility-based substitution factors, as proposed by Demets et al. (2021) or Vadenbo et al. (2017), are less volatile than price-based substitution factors, but determining them is more complex. Because recycled plastics are often used in other applications as virgin plastics, utility-based substitution factors would potentially result in decreasing environmental benefits of the treatment of source-separated plastics (P1, P2, and P3). In addition, recycled plastics may not only replace virgin plastics but also other materials. For example, instead of assuming that reusing PET bottles avoids the production of new reusable PET bottles, it could be assumed that beverage containers made from various materials are replaced (cf. Section 2.2.1 in Supporting Information S1). The environmental performance of P1 (DRS for reusable bottles) would change by more than 5% in all ICs and vary between an increase of environmental benefits by 189% (LU) and a decrease by 44% (OD) (cf. S2.9 in the Zenodo archive). These considerations highlight that substitution choices are crucial for the results of the LCA. The mass-based mono-material substitution factors used in this study because of mass-equivalent use of recycled plastics in products compared to virgin plastics should be considered an upper bound of the potential range of substitution benefits for plastic recycling.

The validity of LCA results is driven by the quality of inventory data and the robustness of applied LCIA methods. The quality of inventory data in the foreground system is determined by data availability. Gaps were filled by data with a deviating temporal or geographical scope or by qualified assumptions (plausibility checks with literature and experts from the industry). Due to the varying quality of inventory data, differences between uncertainties in different pathways and ICs can be observed. The uncertainties are comparatively low (relative standard deviation <10%) in all pathways for the ICs GW, OD, HTnc, PM, IR, RDw, and RDf. However, for example, in the IC HTc high levels of uncertainty can be observed in terms of the impacts of LPW treatment (P3: ± 51%) and MBT of residual waste (P5: ± 155%). To reduce these uncertainties further primary data collection and improved data accessibility in the waste management sector are needed. The uncertainty analysis in the model is limited to inventory data in the foreground system and does not consider parameter uncertainties in the background system or the reliability of applied LCIA methods. JRC (2011b) classifies recommended LCIA methods per IC according to their quality and identifies GW, OD, and PM as “recommended and satisfactory”, IR, POF, AC, TE, AE, and RDf as “recommended but in need of some improvements”, and HTc, HTnc, ET, LU, RDw as “recommended, but to be applied with caution.” Considering both aspects, the calculated uncertainty of LCA results per IC and the maturity of LCIA methods, the validity of results in the ICs GW, RDf, and TE exceeds the validity of results in other ICs considered.

5 | CONCLUSION

LCA of PPWM in Germany 2017 revealed that although only 45% of PPW was recycled, PPWM is associated with environmental benefits in all considered ICs. However, the environmental impacts vary strongly between different pathways. While the treatment of source-separated PPW leads to environmental benefits in all 16 ICs, the treatment of PPW as part of the residual waste is associated with burdens in the ICs GW and RDw. In terms of the treatment of PPW disposed via residual waste, MBT resulting in a refuse-derived fuel for fuel substitution in the cement industry is preferable compared to direct waste incineration due to the benefits from fossil fuel substitution. The perturbation analysis revealed that 24 out of 273 parameters in the PPWMS showed sensitivity ratios above 10%, most of them being relevant in more than one IC. Parameters on source separation are relevant for the results in all ICs. Besides source separation, the quality and quantity of recycled materials as well as the energy recovery from thermal utilization of residues were identified as key factors for the environmental performance of PPWM. Vice versa, the environmental performance of PPWM is less sensitive to changes concerning waste collection and transport distances or technosphere parameters other than treatment efficiencies or substitution parameters (such as the consumption of various auxiliaries). The results of the prospective LCA reveal that in 10 out of 16 ICs (GW, OD, HTc, HTnc, POF, AC, TE, FE, ME, and RDf) a decrease of environmental benefits occurs due to expected changes in the background system until 2050 mainly due to shrinking savings related to heat, electricity, fuel, and plastic substitution. Separate collection and post-processing of residual waste are identified as key factors further gaining in importance. The results highlight that potential measures for improving the environmental performance of PPWM in Germany should focus on long-term key factors, especially separating PPW from the residual waste (in households or in waste treatment facilities) as well as increasing the quantities and qualities of recycled plastics. Fine-grained analysis of environmental performance mechanisms and the evaluation of system performance in view of changing boundary conditions is key to identify optimal configurations of future plastic waste management and should be extended to further case studies to enable sound decision support on strategies for environmentally robust waste management in view of dramatic anticipated changes in material and energy systems.

ACKNOWLEDGMENTS

Open access funding enabled and organized by Projekt DEAL.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study (S2.1-S2.9) are openly available on Zenodo at https://doi.org/10.5281/zenodo.7669434

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Schmidt, S., & Laner, D. (2023). The environmental performance of plastic packaging waste management in Germany: Current and future key factors. *Journal of Industrial Ecology*, *27*, 1447–1460. https://doi.org/10.1111/jiec.13411