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Potential environmental impacts of a plastic waste export ban in Germany

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Up to 800,000 t/a of plastic waste generated in Germany is exported, of which more than a quarter is packaging. However, a sustainable waste management system aims at treating waste under consideration of environmental benefits generation and the reduction of negative environmental impacts. Thus, this brief research deals with the question to what extent negative environmental impacts could be avoided by an export ban. Further, this brief research serves as a preliminary basis for further discussions and studies in the field of the plastic export ban. Two scenarios were developed based on expert interviews to estimate alternative management for the otherwise exported plastic waste generated in Germany. A consequential life cycle assessment (LCA) was carried out to look into the possible Global Warming Potential changes of such scenarios compared to the current situation scenario. The LCA showed that an export ban in Germany offers the possibility of avoiding up to 80 CO_2-equivalent per ton of exported packaging plastic. However, this would be only possible if most of the plastic packaging that is no longer exported is recycled and not burned for energy production in the case of Germany.

KEYWORDS

circular economy, LCA, plastic, recycling, waste exports, waste management

1 Introduction

The German government has the ambitious goal to achieve greenhouse gas neutrality by 2045 and have only negative emissions by 2050 (Federal Climate Change Act, 2019). One leading action to reach greenhouse gas neutrality is closing material loops. The waste management sector plays an important role in this action since it provides substitutes for fossil fuels and primary materials through e.g. incineration and recycling of waste, avoiding greenhouse gas emissions from primary sources. Germany leads the export of plastic waste in Europe with more than 1 million tons in 2019, followed by Belgium with only half of the waste (476,100 t) and the Netherlands (389,900 t) (Destatis, 2022a). Since 2021, only sorted and recyclable plastics are allowed to be exported to certified recycling facilities (European Comission, 2020); as a result, the number of exported plastics has decreased. But still, almost 800,000 t of plastic waste were exported in 2021 (Destatis, 2022b). The main reasons are the cost and the lack of manpower in Germany leading to an economic advantage of selling certain types of sorted plastic bales, such as low-density polyethylene

Abbreviations: Destatis, German Federal Statistical Office; FU, Functional unit; GWP, global warming potential; MP, mixed plastics; UBA, German Federal Environment Agency (in German: *Umweltbundesamt*).

(LDPE), polystyrene (PS) and mixed plastics (MP), on the global market (Anonymous1, 2022). Exported plastic waste can be included in the German recycling quota since it includes all plastic that is delivered to a recycling plant. This contributes to the compliance of the Germany's Circular Economy Act (Circular Economy Act, 2012), which aims to conserve natural resources and protect people and the environment by e.g., recycling waste (Circular Economy Act, 2012).

However, both non-governmental organizations and nature conservation associations are regularly criticizing the export of waste due to inadequate controls and recycling infrastructures in non-EU countries, leading to negative environmental and social impacts. Therefore, they are calling for a plastic waste export ban outside the EU and stricter controls for intra-European exports (Naturschutzbund Deutschland, 2020; Greenpeace, 2021). Thus, the question arises if a modern circular economy should include only regional waste management or if it should use the global potential. Outsourcing waste treatment to other countries could be an indication that regional load limits have been exceeded and worse alternatives are chosen instead of creating new paths.

To answer this kind of question a life cycle assessment (LCA) can be conducted. The literature review of 14 studies (Heyden und Kremer, 1999; Arena et al., 2003; Al-Salem et al., 2014; Fernández-Nava et al., 2014; Hupponen et al., 2015; Rajaeifar et al., 2015; Dehoust et al., 2016; Yildiz-Geyhan et al., 2016; Ferreira et al., 2017; Gu et al., 2017; Milutinovic et al., 2017; Krüger, 2020; Volk et al., 2021; Keller et al., 2022) showed that only a few of them have looked into the potential environmental impacts of generated plastic in Germany and its regional and global disposal. Further, the LCA studies often differ greatly in their framework conditions, e.g., in their functional unit. Among the reviewed studies, none considered the environmental impacts of plastic waste exports and imports. Some studies mentioned that the export of waste to non-European countries is a quantitative significant part, but without going into more detail regarding its environmental impacts (Krüger, 2020; Volk et al., 2021). In the literature review, only reports of non-governmental organizations and environmental associations were found to list the negative environmental impacts of waste exports (Naturschutzbund Deutschland, 2020; Greenpeace, 2021). Thus, the following research question arises: What are the environmental consequences of a possible export ban on plastic packaging in Germany? To answer this question, a consequential life cycle assessment (LCA) was performed based on the ISO Standard 14040/14044. This brief research also serves as a basis for further discussions and studies in the field of plastic export ban.

This brief research is structured as follows: Chapter 2 presents the methodological approaches for identifying the current situation, scenario development and life cycle assessment. Chapter 3 shows the results of this brief research, starting with the description of the current situation and the developed scenarios, followed by the results of the LCA. Finally, Chapter 4 contains the discussion, main implications and recommendations derived from the results of this brief research.

2 Methods

The study consists of two parts. The first part comprises scenario development based on the experiences of experts. The second part comprises the conduction of a consequential LCA based on the developed scenarios.

2.1 Current situation and scenario development

To determine the current situation of plastic packaging waste management for the year 2022, the last available data for 2019 from the Federal Statistical Office (Destatis) and the Federal Environment Agency (UBA) was analyzed and extrapolated to the current year 2022 (see Supplementary Figure S1 2019 data). Further, interviews with two experts in the field of plastic waste management were conducted. One expert works at an established plastics sorting plant and the other expert took part in a national plastic waste study. The statements of the experts are aggregated and anonymized for data protection reasons. Nevertheless, great importance is given to transparency and traceability in the overall documentation. Based on the interviews, two scenarios were developed to estimate the alternative treatment ways for the exported plastic generated in Germany. The two scenarios were based on two different hypotheses. Scenario 1 considered the current plastic waste management capacities in the country, i.e. there is a limited capacity for recycling plastic waste in the country (Anonymous1, 2022; Anonymous2, 2022), leading to the incineration of part of the plastic packaging waste that is no longer exported. Scenario 2 considered that all plastic packaging waste is recycled to achieve the targeted recycling quote in the country. However, one central aspect of scenario 2 is the need for additional capacity for recycling of additional plastic packaging waste that is no longer exported (Anonymous1, 2022; Anonymous2, 2022).

2.2 Life cycle assessment

The life cycle assessment was carried out based on ISO 14040/14044 (International Organization for Standardizaton, 2006a and 2006b). The function of the product system was defined as the management of plastic packaging waste, which is collected, sorted and then exported. The functional unit chosen for this study was the "*management of 1 t exported plastic packaging waste*".

Since a consequential approach was used, the assumed processes that changed were included in the *system boundaries* as far as possible, beginning with plastic packaging waste entering the system already collected and sorted. The transport processes from the sorting facilities to the respective treatment facilities were subject to change from international transports to national transports based on the given research question. Therefore, the avoided transportation abroad and the additional transportation in Germany was also included in the product system. The transport processes of the residues arising in the recycling plant for further recovery were not included in the modeling assuming that they retain their destiny and the transport length do not change whether it happens abroad or in Germany and therefore is not leading for major change. On the other hand, the avoidance of exports and processes abroad were also considered in the model. The model of the foreground system included the transport and recycling processes. The substitution of energy or primary material was assigned to the background system.

The life cycle inventory data of the foreground systems were taken from the ecoinvent v3.8 consequential database and if necessary adjusted by own calculations (transport processes) and values from

TABLE 1 Used processes from ecoinvent v3.8 and adaptions.

Processes	Used processes from ecoinvent v3.8	Adaptions/comment
Transport		
Land routes	transport, freight, lorry >32 metric tons, EURO5	
Short sea routes (e.g. to Great Britain)	transport, freight, sea, ferry	
Long see routs	transport, freight, sea, container ship	
Recycling		
Recycling of fractions	polyethylene production, granulate, recycled	Adapted for each fraction: Recyclate yields Wagner et al. (2018); Dehoust et al. (2016) electricity and water requirements Dehoust et al. (2016)
Incineration		
Incineration as substitute fuels in cement plant in Germany	treatment of waste polyethylene/polypropylene/polystyrene, municipal incineration	The fact that the energy use of substitute fuels in a cement plant is much higher cannot be considered due to a lack of data
Incineration processes of the residues from the recycling processes	treatment of municipal solid waste, incineration	Residues from recycling processes abroad are incinerated in the country with the highest percentage export mass, as this is assumed to be representative
Landfill		
Controlled landfill	treatment of municipal solid waste, sanitary landfill	Used for non-EU, Turkey was considered a representative country
Littering of the natural environment around the plant	treatment of municipal solid waste, unsanitary landfill, dry infiltration class (100 mm)	

other studies, using the most recent data as possible (Dehoust et al., 2016; Wagner et al., 2018). In cases of uncertainties in the data, sensitivity analysis was carried out. The life cycle inventory data for the background system came exclusively from the validated database ecoinvent v3.8. The geographical and temporal representativeness can be found in the documentation of the database (Weidema et al., 2013).

This brief research considered the impact category Global Warming Potential (GWP) based on the high political and public relevance using the CML method. The software openLCA 1.11.0 was used to calculate the impact categories.

2.2.1 Life cycle inventory

The data sets from the ecoinvent used for the processes transport, recycling, incineration and landfill are shown in Table 1. A detailed description of each process is described below.

Transport: The transport distance from the sorting plants to recycling plants in Germany was considered as 255 km (Dehoust et al., 2016). The transport distance from recycling plants and cement plants in Germany was considered as 200 km (Dehoust et al., 2016). The transport distances of the exports were determined using own assumptions and calculations based on the following approach: A travel distance for all relevant countries was calculated *via* luftlinie.org, with the starting points being the midpoints of the countries in each case. The distances of land and water transport were determined using own assumptions, short ways on the sea where considered as ferry transports and long ways with container ships. Using the percentage mass distribution by country of the individual exported plastic packaging fractions (Destatis, 2022b), a value was calculated for the export per fraction for within the EU and outside the EU. Here, 1 t of the plastic fraction is transported as the reference flow. The used values are listed in Supplementary Table S1 in the supplementary material.

Recycling: For the recycling processes, a data set on the production of high-density polyethylene (HDPE) recyclate in Europe from the ecoinvent v3.8 database was used. Due to a lack of other processes, this was adapted for the other recycling processes. The adjusted values are listed in Supplementary Table S2 of the supplementary material. This process includes the new building of recycling plant, which is relevant for scenario 2, as more capacity is used than is currently available. Due to a lack of data, the different technical standards of the plants in different countries could not be considered but should be mentioned. Another major problem was how to deal with the residues from the recycling processes. While these are completely incinerated in Germany, this is often not the case in non-EU countries for example in Turkey or Malaysia (Angi, 2019; CHen et al., 2021). Turkey is the largest non-EU state which receives exported plastic waste, thus the practices were assumed to be representative (Destatis, 2022b). According to OECD (2019) and Angi (2019), 61% of mixed municipal waste in Turkey was mainly sent to landfills. In this study carried out, it was assumed that about 60% of the residues from the recycling processes are also be sent to landfills. Another 10% are dumped uncontrolled due to littering of the landscape around the plants (Anonymous2, 2022). The remaining 30% are incinerated in waste incineration plants.

Incineration: In the incineration processes, a distinction was made between the incineration of the sorted fractions as a recovery route, which only occurs in Germany (see scenario development in Chapter 3.1) and the incineration of the residues from the recycling process, which is happening abroad and would also happen in Germany (see scenario development Chapter 3.1), as previously described in the recycling process.

Landfill: With regard to the landfill, only part of the residues from recycling processes outside the EU is landfilled (OECD, 2019). Turkey was assumed to be a representative country since it is the largest country that receives plastic waste from Germany outside the EU (Destatis, 2022b).

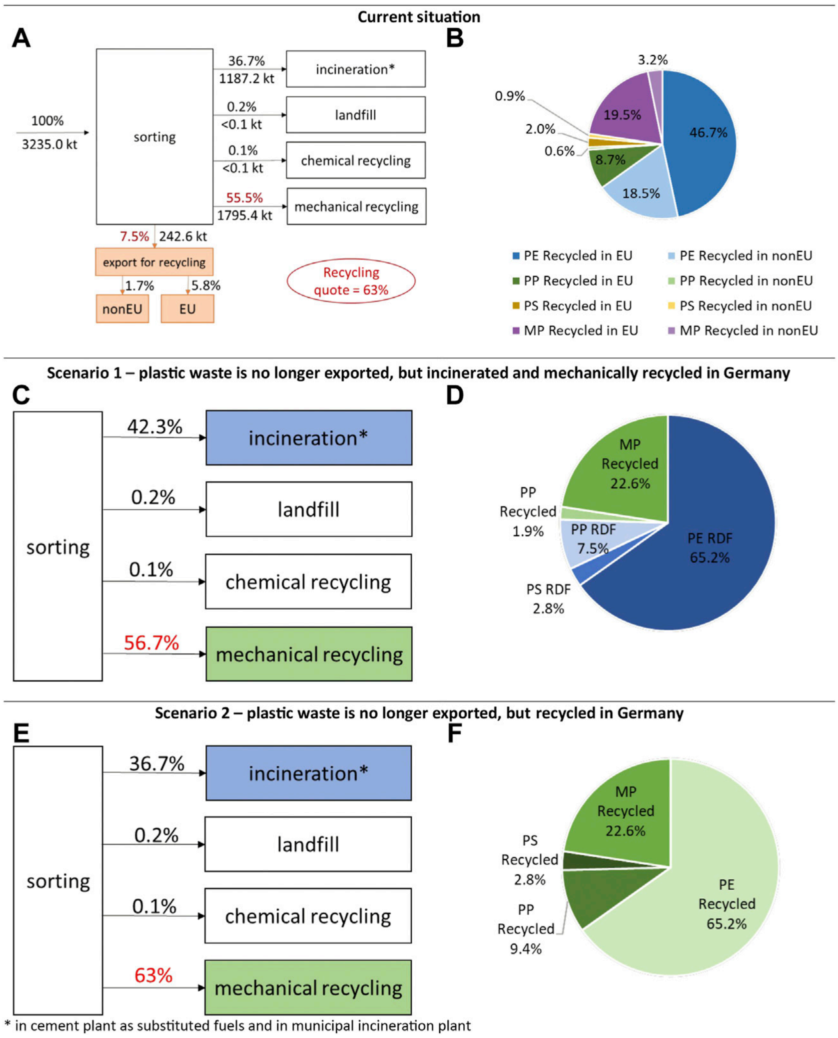

FIGURE 1
Overview of current situation and scenarios. **(A)** and **(B)** Figures for the current situation; **(C)** and **(D)** Figures for scenario 1—areas in blue indicate the types of plastics being incinerated in Germany, areas in green indicate types of plastics being recycled in Germany; **(E, F)** Figures for scenario 2—areas in green indicate types of plastic being recycled in Germany. (PE: polyethylene, PP: polypropylene, PS: polystyrene; MP: Mixed plastic, RDF: refuse-derived fuel). Values in red indicate the achieved recycling quote in each scenario.

An auxiliary process was created for each scenario to divide the plastic packaging waste into different fractions and their recovery routes. The new processes arising in Germany (different for each scenario, for scenario 1 namely recycling, incineration, and incineration of recycling residues; for scenario 2 recycling and incineration of recycling residues) were included positively and the processes previously occurring abroad (the same for both scenarios, namely transport, recycling and incineration/landfill of recycling residues) were included negatively in the model. The values used for the auxiliary process are available in Supplementary Table S3 of the supplementary material.

2.2.2 Sensitivity analysis

Significant parameters were identified and further investigated in the sensitivity analysis, namely the ratio of incineration to recycling of PE in scenario 1, the recyclate yield in both scenarios, and the substitution of primary by secondary material in both scenarios.

Ratio incineration to recycling: In Scenario 1, it was assumed that PE and PS are completely incinerated because there are no additional capacities for their recycling in Germany according to the interviews. Since the recycling of PE made up a large part of the overall result, the extent to which this assumption influences the result was investigated. For this purpose, the ratio of incineration to recycling of PE in Germany was varied as 100:0; 80:20, 50:50, 20:80 and 0:100.

Recyclate yield: As shown in other studies, the recycling process turns out to be more environmentally friendly than other energy recovery processes (Hupponen et al., 2015; Ferreira et al., 2017). Due to a lack of data, the same quantities were assumed for both plants located in Germany and non-EU. However, it can be assumed that the recycling plants in non-EU countries do not meet the same technical standards as the plants in Germany (Anonymous2, 2022) and therefore have a lower recycling yield for the same input quantity (Anonymous2, 2022). To test the influence of this yield, the yield of all fractions in non-EU countries was reduced by 20%, whereby the 20% is only an example of a change.

Substitution ratios: Another relevant factor for the GWP result is the substitution of primary by secondary material. In the study, it was assumed that 1 t of recyclate substitutes 1 t of primary material. However, in reality, recyclates might have lower quality compared to the primary material, not being able to replace 100% of the primary material (IK, 2019). Therefore, in the sensitivity analysis, the amount of primary material that can be replaced by 1 t of recyclate was varied as follows: 1 t of recyclate replaces 0.8 t of primary material, 1 t of recyclate replaces 0.5 t of primary material, and 1 t of recyclate does not replace any primary material. This was adjusted for all recycling processes in Germany and abroad.

3 Results

3.1 Scenario development

3.1.1 Current situation: Plastic packaging management in Germany in 2022

Figure 1A shows the estimated plastic packaging waste management for 2022 (current situation), with 3,235 kt of plastic packaging waste entering in the sorting plants. According to the interviews, it was assumed that the legally prescribed recycling rate of 63% source would be achieved in 2022, as in previous years (Anonymous1, 2022; Anonymous2, 2022). The export rate fell by 25% in 2021 due to the addition of the Basler conventions (European Comission, 2020) but is not expected to fall in 2022 as no new legislation will come into force. Therefore, in 2022 7.5% of the sorted plastic packaging waste was estimated to be exported, mainly to EU countries like Poland and the Netherlands but also to non-EU countries, like Turkey and Malaysia. The detailed distribution of the 7.5% per fraction and EU or non-EU is shown in Figure 1B (Destatis, 2022b).

3.1.2 Scenario 1: Use of current capacities

The first scenario was based on the current capacities of recycling plants in Germany. The industry has high ambitions to expand the capacities of the plants. However, according to the German immission control law, the expansion of new plants is associated with complex approval procedures that can take more than 2 years (Federal Immission Control Act, BImSchG, 2013; Anonoymous1, 2022). If the export of plastic packaging were to be stopped, the amount of plastic packaging to be recycled would suddenly increase by more than 7% compared to the current situation. In this scenario, it was assumed that capacities have not been expanded and that only current capacities could be used. The resulting overall situation for scenario 1 is presented in Figure 1C. The additional 7.5%, which is now treated in Germany is partly incinerated and partially mechanically recycled. The detailed distribution per fractions and treatments of the additional 7.5% is shown in Figure 1D. The assumed capacities were based on expert interviews. It was assumed that there is little to no capacity in Germany for LDPE and PS, as it is more lucrative to have these plastics recycled abroad (Anonymous1, 2022; Anonymous2, 2022). These types of plastic would therefore be recovered as energy. Since waste incineration plants in Germany are also at their capacity limits (Briese and Gatena, 2020), it was assumed that the LDPE and PS waste would be incinerated as substitute fuels in cement plants. For mixed plastic waste there are several recycling plants with enough capacities in Germany available (Anonymous2, 2022). There are also for PP packaging possibilities to recycle in some larger plants in Germany, but no plants are specialized only in PP as is the case for HDPE. For this scenario, it was assumed that a part of 20% of the exported PP could be mechanically recycled. The remaining 80% would be burned as a substitute fuel in cement plants, like LDPE and PS.

3.1.3 Scenario 2: Compliance with the recycling rate

According to the German Packaging Act (VerpackG), operators involved in the system are obliged to recycle the packaging placed on the market in accordance with the recycling quotas. If they cannot prove this, they may face fines of up to one hundred thousand euros (Packaging Act, 2017). If exports are banned, it would still be a top priority to achieve the legal recycling rate. In 2021, the recycling quota was achieved and even slightly exceeded, but only because the exported plastics could be counted as mechanically recycled. A comparable situation was therefore assumed in 2022. Assuming an export stop, the system operators would make efforts to recycle the otherwise exported goods in Germany in order to continue to meet the recycling rate. This is also shown in the resulting overall situation of scenario 2, in which 63% goes to recycling (see Figure 1E). The distribution of the fraction of the additional 7.5% is shown in Figure 1F.

3.2 Life cycle assessment

3.2.1 Impact assessment

The following results show the potential environmental impact for GWP of the changes (delta) of each scenario compared to the current situation. Scenario 1 (use of current capacities) shows an increased impact of the GWP (approximately 2,000 kg $CO_{2\text{-eq}}$ per FU) (see Figure 2A), which can be traced back to the incineration process in Germany due to the lack of recycling capacities in the country and, therefore, the missing substitution of primary material in the export countries. Thus, under this scenario, an export ban would not be environmentally beneficial.

On the other hand, scenario 2 (compliance with recycling rates) seems to be environmentally beneficial, saving 80 kg $CO_{2\text{-eq}}$ per FU (see Figure 1C). Compared with scenario 1, the treatment of waste in Germany is of great importance. This is particularly evident when comparing the changes in transport processes and treatment processes between the two scenarios (see Figure 2). Transport processes have only a minor impact as soon as the treatment processes change, as they do in scenario 1. To save negative environmental impacts, the plastic packaging waste that is no longer exported must be recycled in Germany. Recycling the total amount of plastic packaging waste in Germany, as modeled in scenario 2, over 20 million kg of greenhouse gas emissions could be saved. This amount corresponds to 0.003% of the total greenhouse gas emitted in Germany in 2021 or 0.3% of the greenhouse gas emissions generated by waste management in Germany in 2021 (UBA, 2022). Figure 2D shows that these savings are based not only on transport but also on the more controlled handling of leftovers in Germany.

3.2.2 Sensitivity analysis

The ratio incineration to recycling of PE has a large influence on the overall result of this ratio, as presented in Figure 3A. If the entire exported quantity of PE could be recycled in Germany after all, there would even be a saving of the environmental impacts investigated by scenario 1. This shows how relevant the recycling path of the plastics in Germany is for an assessment of the environmental impacts. The incineration process is also significant when it comes to the environmental assessment of the plastic cycles. This becomes clear in scenario 1 or when dealing with the residues in scenario 2. The positive impact is again very dependent on the heat and

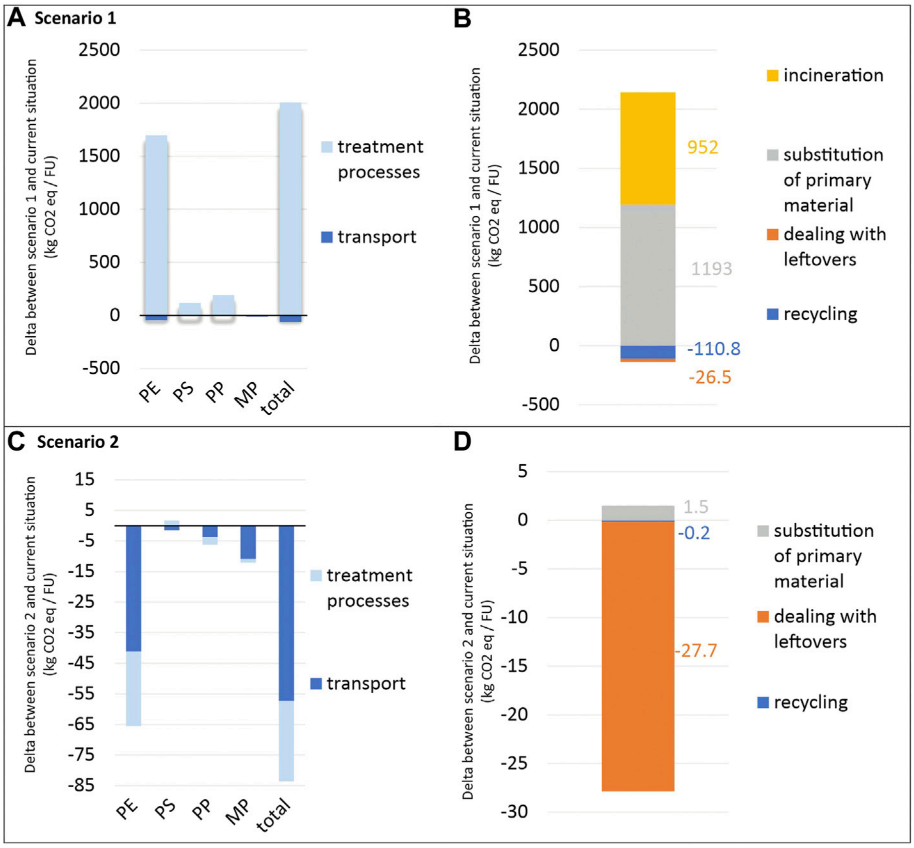

FIGURE 2
Results of the impact assessment for GWP for both scenarios. Breakdown of results into treatment and transport processes for scenario 1 **(A)** and scenario 2 **(C)** and more detailed breakdown of individual treatment processes for scenario 1 **(B)** and scenario 2 **(D)**. The results are presented as a delta between the scenario and the current situation.

energy production and which electricity mix is replaced with it, e.g. substituting the energy mix of Poland with incinerating plastic can save more GWP than substituting the German energy mix. This is also assessed as significant in other studies of waste management systems (Dehoust et al., 2016; Keller et al., 2022).

The influence of the recyclate yield on the GWP results for each scenario is shown in Figure 3B. Lower recyclate yields abroad would lead to lower substitution ratio, i.e. higher GWP. For an export ban under this condition, the difference between the GWP in Germany compared to the GWP abroad would not be as high as if the recyclate yield abroad would be high. To be able to make better estimations about saving potential, validated data on the recyclate yields of individual plants in Germany and abroad are necessary.

With regard to the substitution of primary material by secondary material, it turns out that for scenario 1 it is very decisive that the elimination of these processes in other countries would lead to an increase in GWP. If less primary material can be replaced by secondary material, the additional GWP emitted (i.e. the delta between the GWP in Germany and abroad) would decrease (see Figure 3C). For scenario 2, there would be only a slight change in the savings, as the quantities of primary materials replaced in Germany and abroad would balance each and would not have a great influence on the GWP results. To make a more precise statement about the influence of the substitution of primary materials, an analysis of the plastics markets and an analysis of the use of recyclates in the production of plastic materials in the different countries is necessary.

4 Discussion and conclusion

The figures for exported plastic packaging waste have shown that no change would be expected if there are no legal requirements. In the past, changes in imported or exported waste only occurred after new legal requirements came into force (e.g. import stop of China and the addition to the Basel Conventions) (Media Service und Verlag GmbH, 2018; European Comission, 2020). A politically desired and legally enforced export ban should therefore be well considered and justified.

To assess the environmental impacts with regard to GWP of such an export ban, two scenarios were developed. It should be mentioned that the scenarios here can only be considered as examples for an initial overview. Although scenario 1 has uncertainties, it could be seen as a “worst-case” scenario, whereas scenario 2 could serve as a “best-case” scenario. To be able to make realistic and more detailed recommendations for action, further research would have to be carried out on the current capacities of recycling plants and planned new construction as well as the expansion in Germany, considering future scenarios.

An export ban could lead to savings in greenhouse gas emissions, but only if the majority of the exported plastic packaging waste would be

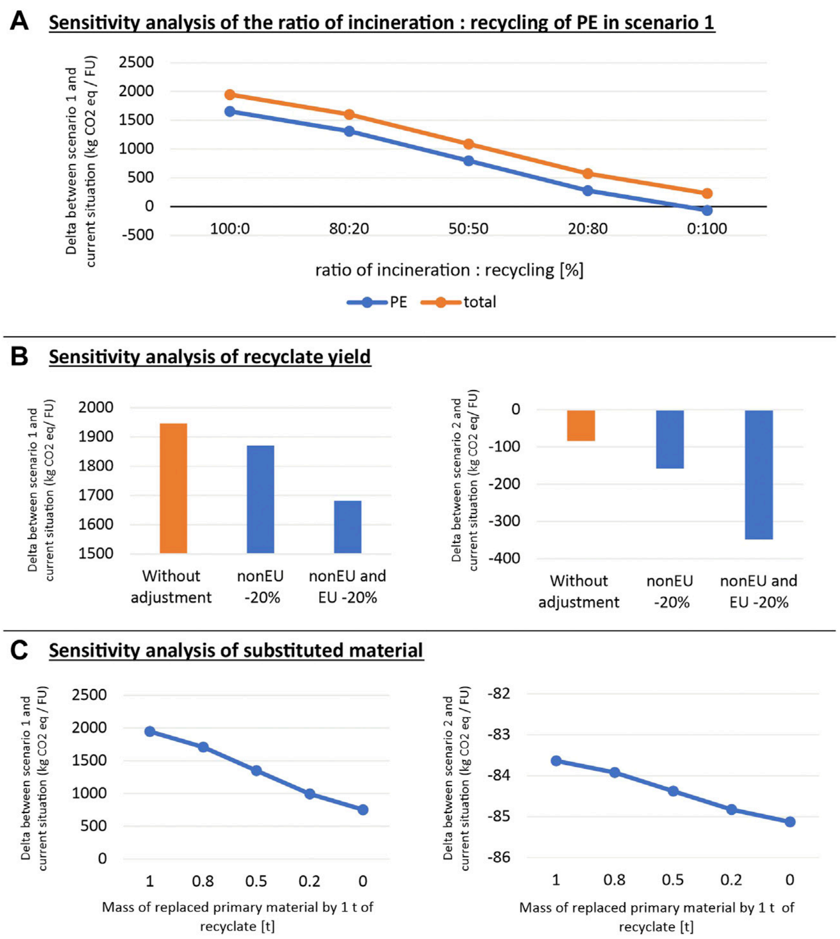

FIGURE 3
Sensitivity analysis for ratio of incineration to recycling of PE in scenario 1 **(A)**; recyclate yield **(B)** and substituted material **(C)**.

recycled in Germany and not recovered elsewhere. This is in line with the studies on waste management systems analyzed in advance, which all rate recycling as environmentally beneficial (Hupponen et al., 2015; Ferreira et al., 2017). Some studies cite the transport processes as irrelevant, as they hardly contribute to the environmental impacts (Hupponen et al., 2015; Gu et al., 2017). This can be confirmed here insofar as the recycling route is more decisive than the transport processes and should therefore be in the foreground when considering an export ban.

This result can serve as a basis for information and an initial insight. However, this study should be seen as an initial overview, due to uncertainties, particularly regarding the differences in the procedures and qualities of the recycling plants in Germany, the EU and non-EU countries, as the sensitivity analysis has also shown. Furthermore, the sensitivity analyses have shown the high influence of the capacities of the recycling plants in Germany and the partial or complete substitution of the primary material by the recyclate obtained. Additionaly only legal and tracked waste exports were considered in this study. A large amount of illegal exports was left out due to the opaque data situation (Interpol, 2020; Olley, 2021).

In addition, this is a relative approach and potential environmental impacts are to be understood as such and do not predict actual environmental impacts and hazards. Any results, conclusions and recommendations drawn from them can therefore serve as a basis for further information for stakeholders. However, if the intention is to derive far-reaching strategies for action, a critical review according to ISO 14040 and 14044 and possibly further studies should be carried out.

The results of the literature research and evaluation of the expert interviews have shown that the current capacities of the recycling plants in Germany would not allow complete recycling of the plastic packaging waste exported so far. An expansion of current capacities would therefore be necessary before deciding on an export ban.

In order to make a more comprehensive recommendation on an export ban on plastic packaging waste, it would not be sufficient to carry out only an environmental assessment. Economic and especially social consequences in Germany, but also in the import countries, should be examined more closely.

Ultimately, it could be argued that the possible savings of negative environmental impacts by optimizing the waste management of plastic packaging in Germany only account for a very small part of the total climate impacts. However, in order to achieve climate neutrality by 2045, it is necessary to become active in all areas and to analyze and demonstrate possibilities for saving negative environmental impacts. This work has shown that there is potential for savings in the handling of exported plastic packaging waste. Finally, a more in-depth analysis of the possibility of stopping the export of plastic packaging waste is recommended.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

RS: Research conduction, article writing TH: Research support, article review AL: Research support, article review.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmtec.2023.1077313/full#supplementary-material

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