Environmental impacts of the global plastic waste trade: assessment and mitigation

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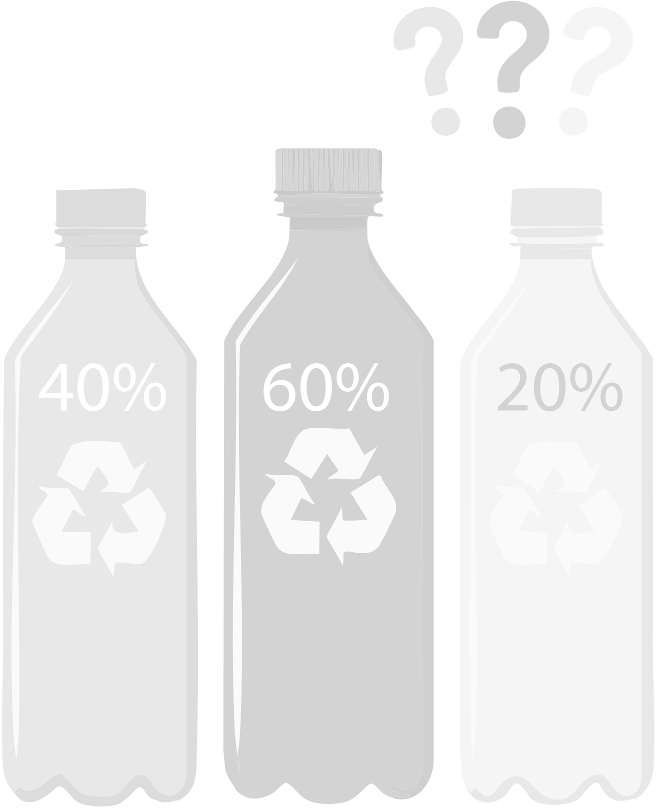
Chapter 3

Economic viability requires higher recycling rates for imported plastic waste than expected



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Abstract

The environmental impact of traded plastic waste hinges on how it is treated. Existing studies often use domestic or scenario-based recycling rates for imported plastic waste, which is problematic due to differences in recyclability and the fact that importers pay for it. We estimate the minimum required recycling rate (*RRR*) needed to break even financially by analysing import prices, recycling costs, and the value of recycled plastics across 22 leading importing countries and four plastic waste types during 2013–2022. Here we show that at least 63% of imported plastic waste must be recycled, surpassing the average domestic recycling rate of 23% by 40 percentage points. This discrepancy suggests that volumes of recycled plastics in the global North-to-South trade are underestimated. The country-specific *RRR* provided could enhance research and policy efforts to better quantify and mitigate the environmental impact of plastic waste trade.

3.1 Introduction

Over the past decades, increasing globalization has fragmented supply chains, making the assessment of life-cycle environmental impacts more challenging(Jakob et al., 2021; Skelton, 2013; Timmer et al., 2014). A similar trend has emerged in waste management. Since 2019, traded waste plastics have amounted to approximately five million tons per year(Our World in Data, 2022). Typically, this waste is exported from high-income countries to low-income countries, where labour and treatment costs are lower(Geyer et al., 2017). However, such exports to the Global South have raised major concerns due to potential mismanagement, which can have severe negative impacts on the environment, ecosystems, and human health(Geyer et al., 2017; Letcher, 2020; Meijer et al., 2021; Wen et al., 2021). Mismanaged plastic waste contributes to river pollution and is a significant factor in the 'plastic soup' found in oceans(Nava et al., 2023).

Recent publications indicate that globally less than 10% of waste plastics are recycled(Geyer et al., 2017). A significant amount of plastic waste is mismanaged in countries with underdeveloped waste collection and treatment systems(Jambeck et al., 2015). For example, over half of the plastic waste in Indonesia is incinerated without recovering energy, and 5% is disposed of in uncontrolled dumpsites(World Economic Forum, 2020). Evidence shows that more than 60% of marine litter plastics emissions annually come from the Philippines, India, Malaysia, and Indonesia(Meijer et al., 2021). Much of this plastic waste treated in the Global South originates from the Global North, contributing to environmental plastic waste emissions(Guardian, 2019).

In response to these concerns, China, a major importer of plastic waste, implemented a plastic import ban in 2018(Wen et al., 2021). This decision redirected plastic waste exports to other countries, notably Malaysia, Indonesia, Turkey, and Vietnam. To address potential negative impacts and prevent mismanagement abroad, the European Union (EU) has recently considered a ban on plastic waste exports to non-OECD countries(European Commission, 2024), adhering to the principle that countries should be responsible for the proper treatment of their own waste(Jakob et al., 2017).

While the global plastic recycling rate remains low, there is an implicit assumption that traded plastic is primarily recycled(Our World in Data, 2022). However, accurately determining the recycling rate for imported plastic waste in receiving countries is challenging due to measurement difficulties. Existing studies often rely on assumed domestic or scenario-based recycling rates, which lack robust data support. For example, Wen et al. quantified the shift in environmental impact of plastic waste imports from China to Southeast Asia, using assumed domestic recycling rates ranging from 10% to 40% for five Southeast Asian countries(Wen et al., 2021). Similarly, Bourtsalas et al. estimated the environmental impact of treating imported plastic waste in the USA, using widely varying recycling rates from 8.7% to 50%(Bourtsalas et al., 2023). Bishop et al. faced a lack of official data on exported plastics from Europe, leading them to use a broad range of recycling rates from 50% to 90%(Bishop et al., 2020). This reliance on domestic or scenario-based rates highlights the urgent need for comprehensive and transparent data to guide policy and research effectively.

Moreover, replacing the recycling rate of imported plastic waste with the domestic average is questionable for two main reasons. Firstly, domestic plastic waste often comes from diverse sources, resulting in heterogeneous and difficult-to-recycle mixtures, particularly in regions with inadequate or partial waste separation. In contrast, imported plastic waste is typically more concentrated and uniform, as it is pre-selected for exporting. Secondly, the UN Comtrade database shows that importing countries pay for plastic waste, indicating its economic value (see Fig. 3.1)(UN Comtrade, 2019). If these imports were not processed into valuable recyclates—i.e., if they were primarily dumped or burned—the importing companies would face significant financial losses, making it unsustainable for them. Therefore, any viable approach must ensure that at least part of the imported plastic is converted into economically valuable outputs through recycling to offset initial costs.

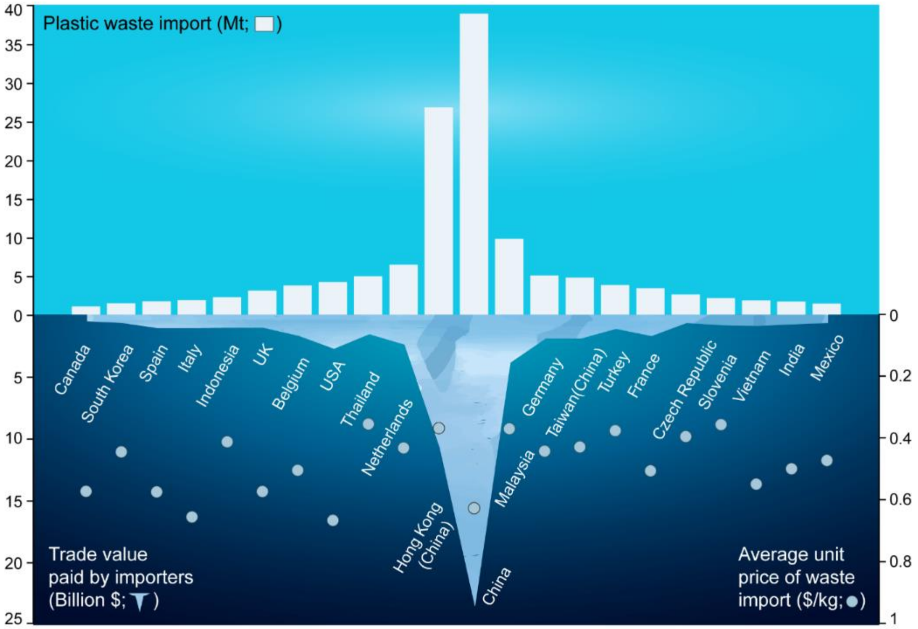

Figure 3.1 Accumulated plastic waste imports, trade values, and average unit prices paid by the top 22 importers from 2013 to 2022. The trade value reflects the cost, insurance and freight (CIF) price. The average unit price of waste import is calculated based on the weighted values of four plastic waste types (PE, PS, PVC, and others) across the years. The original trade data, including net weight and trade value, are sourced from the UN Comtrade database.

In this work, we introduce a novel approach by defining the *Required Recycling Rate* (*RRR*). We estimate the *RRR* for the 22 largest plastic waste-importing countries from 2013 to 2022 based on the economic break-even point, where the revenue from recycling matches the costs of imports and the recycling process (labour, electricity, and real estate rentals(Larrain et al., 2021; Uekert et al., 2023)). We assume that recyclates can be sold at prices comparable to primary plastics and consider physical losses throughout the recycling process(Hopewell et al., 2009; OECD, 2022c). Import costs and primary plastic values are derived from 186,861 bilateral trade records for four plastic wastes (PE, PS, PVC, and others) and six primary plastics (HDPE, LDPE, PS, PVC, PET, and PP) from the UN Comtrade database. Here, "recycling" specifically refers to mechanical recycling, the predominant method for recycling imported waste in Global South countries(Plastic Europe, 2019; Rosenboom et al., 2022). Our findings indicate that the *RRR* for imported plastic waste in the 22 research countries significantly surpasses their reported national recycling rates. Sensitivity and Monte Carlo-based uncertainty analyses further confirm the robustness of these results.

3.2 Results

3.2.1 Required recycling rates across four plastic wastes and 22 countries

Our analysis shows that at least 63% of the imported plastic waste must be recycled to offset the costs. However, the *RRR*s vary across countries and plastic waste types (Fig. 3.2).

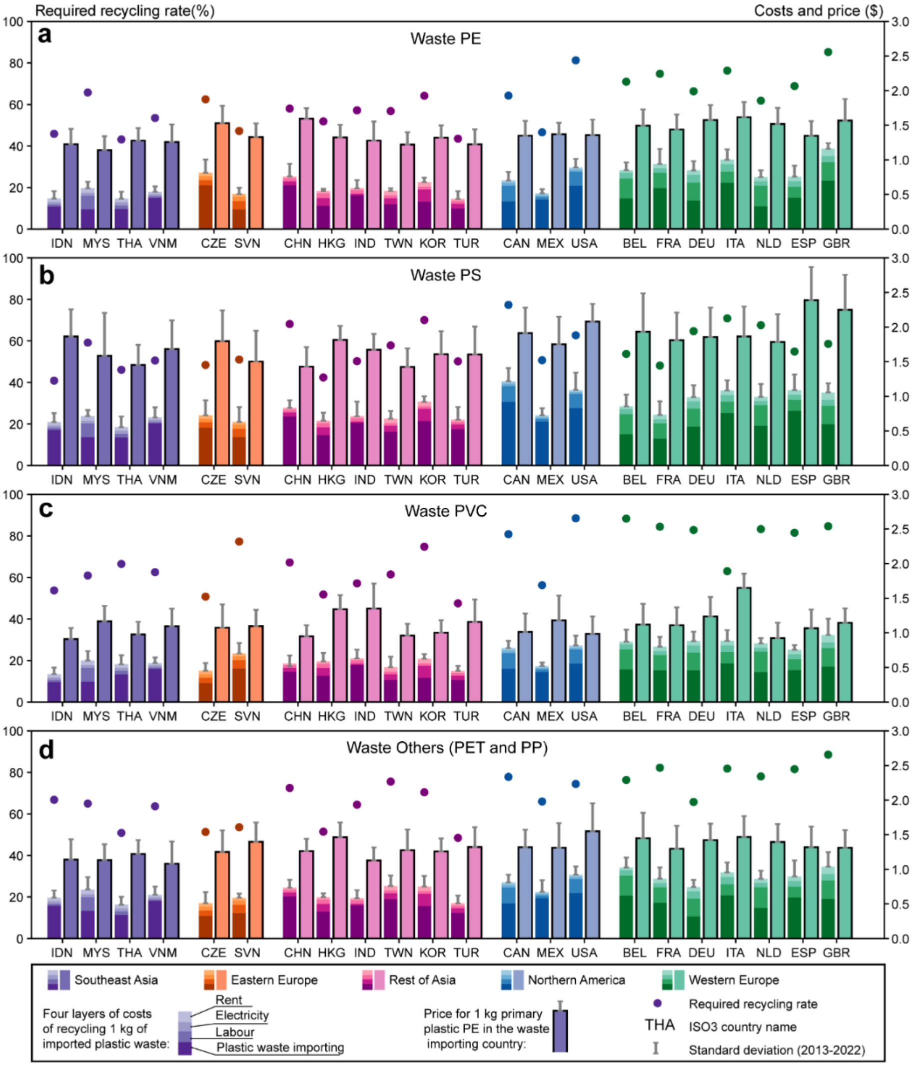

Figure 3.2 Required recycling rate of imported plastic waste by country and plastic waste type. The 22 research countries are geographically divided into five country groups. For each country, the left bar represents the costs associated with recycling 1 kg of plastic, while the right bar shows the value of 1 kg of recycled plastic. The *RRR* calculated using

mirror trade data is shown in Supplementary Fig. B1, with comparisons detailed in Supplementary Table B1. The annual *RRR* from 2013 to 2022 across 22 research countries and four plastic waste types is presented in Supplementary Figs. B2–5.

Due to the significant gap between recycling costs and product prices, countries in Asia and Eastern Europe have the lowest *RRR* for imported plastic waste, starting at around 40%. Specifically, Thailand, Turkey, and the Czech Republic have the lowest *RRR* benchmarks for their respective plastic waste types, ranging from 40% to 50%. In contrast, higher *RRR*s are needed for Western Europe and North America, reflecting limited profitability for recycling imported plastic waste in these regions. The highest *RRR*s are observed in France, the UK, Belgium, and Canada, with average values between 61% and 82% for all plastic waste types. For comparison, the mechanical recycling costs collected from other literature sources are detailed in Supplementary Table B2.

Examining distributions among four plastic waste types reveals that PE and PS waste have the lowest *RRR*, averaging 10% to 20% lower than those for PVC and 'Others' within the same region. PVC recycling is already hindered by challenges such as its chlorine content and contamination issues(Fagnani et al., 2023). Our results further imply that recycling PVC is less economically competitive compared to other plastics, due to a narrower profit margin between recycling costs and primary plastic prices. This results in *RRR*s for PVC that are on average 40% higher than for PE from 2013 to 2022. The higher *RRR*s for 'Others' plastic waste (Fig. 3.2d) are attributed to greater variability in recycling costs and primary plastic prices, as illustrated in Fig. 3.4, with mixed plastic waste falling into this category.

The variation in *RRR* across different types of plastic waste serves as a crucial market signal for each country's plastic waste import structure. For example, the Netherlands demonstrates a significant contrast in *RRR* between waste PVC and waste PE, with *RRR* of 83% and 62% respectively. This difference suggests implicitly higher recycling costs and narrower profit margins in the PVC recycling market compared to the PE recycling market in the Netherlands. Confirming this trend, the Netherlands evidenced higher imports of waste PVC (3 Mt) compared to waste PE (0.1 Mt) during the period 2013–2022. Similar import structures are observed in countries such as Germany, the USA, France, and Belgium. In contrast, *RRR* differences across plastic waste types are less pronounced among countries in the global South. For instance, *RRR*s across four plastic waste types range from 50–64% in Vietnam, 40–50% in Turkey, and 50–64% in India. Supplementary Table 1 provides a detailed comparison of *RRR* differences among plastic waste types across countries.

Although import costs are the largest component of overall expenses and are often seen as a major factor influencing plastic waste trade(European Environment Agency, 2023), they do not fully explain the observed differences in *RRR* between Europe and Asia as effectively as labour costs do. For instance, Germany, a major plastic waste importer in Western Europe, faces import costs ranging from \$0.33 to \$0.57 per kilogram across the four plastic types assessed. These costs are only slightly higher than those of large Asian importers such as Turkey (\$0.27–\$0.53) and Thailand (\$0.27–\$0.46). In contrast, labour costs, the second largest cost factor, are significantly higher in Western Europe. Recycling 1 kg of imported plastic waste in Germany incurs average labour costs of \$0.26 from 2013 to 2022, which is approximately four times higher than in Turkey (\$0.067) and five times higher than in Thailand (\$0.052). It is important to note that these cost-related statistics, collected at the country level, may not fully capture regional variations within countries.

3.2.2 Comparison between required recycling rate and domestic average

A notable discrepancy emerges when comparing the calculated *RRR* with the collected national plastic recycling rates across 22 countries (see Supplementary Table B3). The *RRR* averages 63% for the period between 2013 and 2022, which is 40% higher than the average national plastic recycling rate of 23% (Fig. 3.3a). The *RRR* average and the domestic average are weighted by import mass across countries and plastic waste types and by the annual domestic plastic waste generated across countries, respectively (refer to Supplementary Table B3). This discrepancy subsequently affects the estimation of the amount of plastics recycled from the waste traded from the Global North to the Global South (refer to Fig. 3.3b, with the countries involved detailed in Supplementary Table B4). Using the national plastic recycling rate, the annual amount of recycled plastics from the plastic waste trade from the Global North to the Global South averaged 0.37 million tonnes per year (Mt yr^{-1}) over the past five years (2018–2022). In contrast, the annual recycling volume surges to 1.04 Mt yr^{-1} if the *RRR* is used, an increase of 0.67 Mt, roughly equivalent to France's recycled plastics output in 2022(Plastics Europe, 2023).

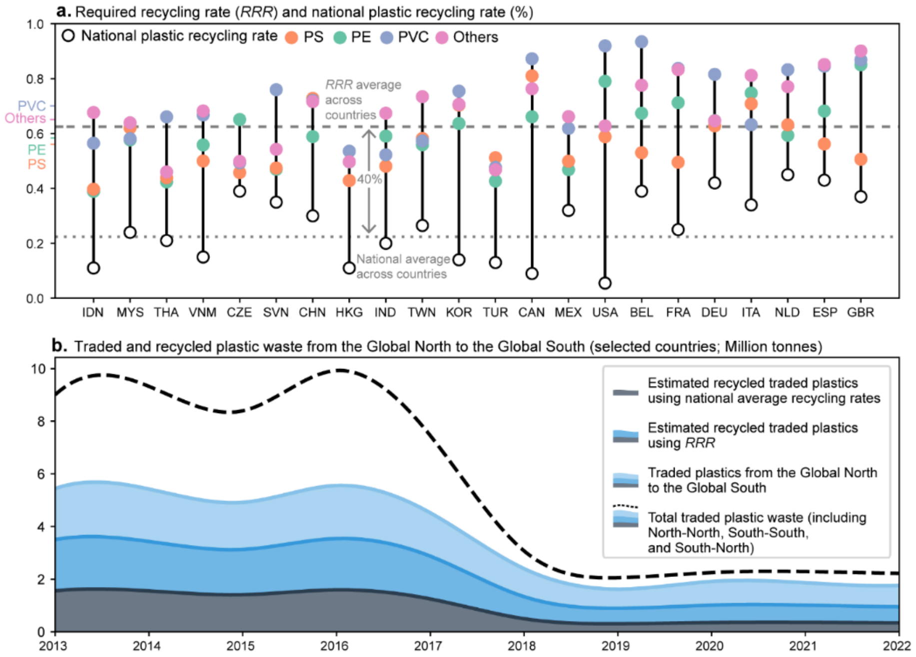

Figure 3.3 The difference between required recycling rates and national plastic recycling rates across 22 countries. Fig. 3.3a illustrates the variations in average *RRR* across countries and plastic types. The dashed line represents the average *RRR* across countries, weighted by the total import mass across countries. The plastic waste type label on the Y-axis displays the average *RRR* of each plastic waste type, weighted by the import mass of each plastic waste type across countries. Additionally, the dotted line below denotes the country's average plastic recycling rate, weighted by the annual domestically generated plastic waste across countries. Mass data corresponding to Fig. 3.3a are provided in Supplementary Table B3. A comparison of the average *RRR*, weighted by either trade mass or trade value and using both trade and mirror trade data, is shown in Supplementary Table B5. Fig. 3.3b illustrates how these differences impact the estimates of recycled plastics from the waste traded from the Global North to the Global South between 2013–2022 (countries involved are listed in Supplementary Table B4). The trade data originate from the UN Comtrade database. The results from Fig. 3.3a–b calculated using mirror trade data are shown in Supplementary Fig. B6.

3.2.3 Assessing sensitivity across factors and regions

We conducted a sensitivity analysis to examine how six key variables influence our results across different countries and plastic waste types (Fig. 3.4). The analysis considers both pessimistic and optimistic scenarios, representing each variable based on their minimum and maximum values observed from 2013 to 2022.

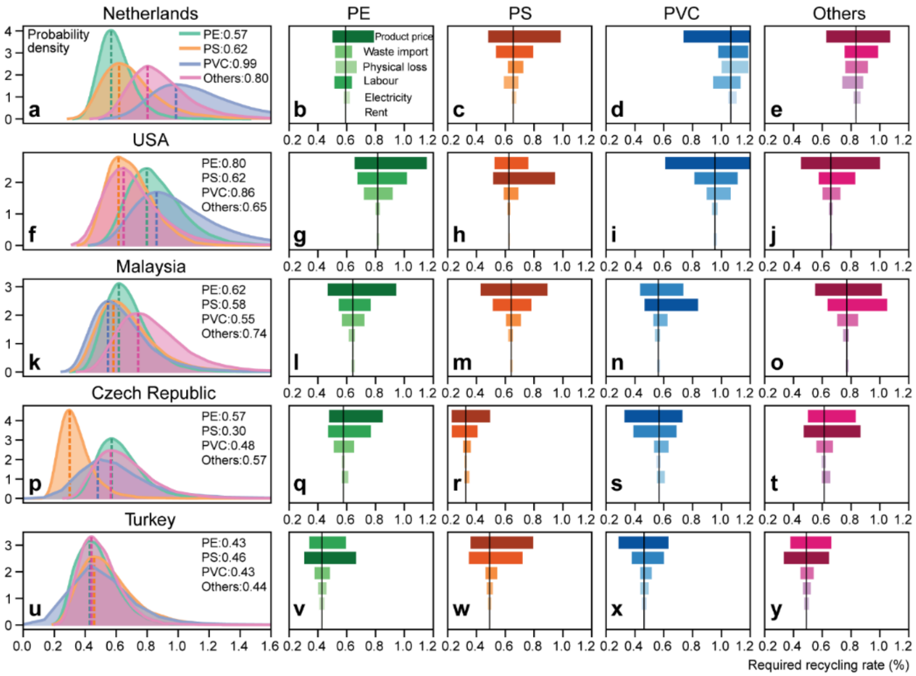

Figure 3.4 Sensitivity analysis and Monte Carlo simulation of required recycling rate across four plastic types in five selected countries. The results using the mirror trade data are shown in Supplementary Figs. B7. The length and colour depth of the horizontal bars represent the range of sensitivity results.

On average, fluctuations in the product price for recycled plastics have the greatest impact on the calculated *RRR*, varying between -25% and +36%. Variations in *RRR* are also significantly affected by import costs, with changes ranging from -21% to +29%, and physical losses, ranging from -8% to +11%. Labour costs contribute to fluctuations of -4% to +4%, electricity costs from -1% to +2%, and rental costs from -0.9% to +1%. Regional differences are particularly notable in labour costs, with pronounced variations between Europe and Asia. For example, the Netherlands shows fluctuations ranging from -11% to +6% (Fig. 4b-e), compared to narrower ranges of -4% to +2% in Malaysia and -1% to +1% in Indonesia. Additionally, the analysis reveals notable variations across waste types, particularly for PVC and 'Other' types. These variations are attributed to fluctuations in product prices and import costs for these waste types over the past decade, as well as the more complex composition of 'Other' plastics.

3.3 Discussion

The divergent recycling rates across countries result in varied estimations of recycled volumes from plastic waste trade, complicating the assessment of its environmental impacts. Notably, the *RRR* averaged approximately 63% across 22 major importers and four plastic waste types from 2013 to 2022, significantly higher than the average domestic recycling rate of 23%. Moreover, country-specific *RRR* values exceed those reported in previous studies based on domestic recycling rates. For example, while Wen et al. (2021)(Wen et al., 2021) assumed a recycling rate of 38% for imported plastic waste in Malaysia for 2018, our study indicates a minimum required recycling rate in Malaysia of 58% (PE and PVC), 62% (PS), and 64% (Others) over the period from 2013 to 2022. This discrepancy suggests a potential underestimation of recycled plastic volumes in waste-importing countries. Such variations in recycling rates can lead to differing estimates of the environmental impacts associated with plastic waste trade. Higher recycling rates suggest reduced losses and emissions, as well as decreased reliance on virgin plastic production(Bachmann et al., 2023). For instance, Wen et al.(Wen et al., 2021) assessed the environmental impact of China's plastic import ban using domestic recycling rates for imported plastics, estimating the net carbon emissions of treating traded plastic waste in 2018 at 0.13 Mt CO_2-eq. In a scenario reflecting a 50% increase in countries' recycling rates, closely aligning with our calculated *RRR* for the same period, this figure dropped to -60 Kt CO_2-eq.

RRR enhances the accuracy of modelling the fate and impacts of traded plastic waste, which is crucial for scientific research and policy implementation. By indicating the share of recycling versus non-recycling, *RRR* provides valuable data for measuring the environmental impacts of the global plastic waste trade, particularly in waste-importing countries. Moreover, annual *RRR* data across countries and plastic waste types sheds light on how external events influence the global plastic waste trade. For instance, a notable increase in *RRR* across many countries in 2020 coincided with a drop in crude oil prices(Le et al., 2021), suggesting that lower prices for virgin and recycled plastics necessitated a higher *RRR* to cover costs and achieve profitability. In terms of policy implications, *RRR* can assist waste-importing countries in formulating and adjusting their recycling targets. Instead of relying on domestic average recycling rates, which are often based solely on domestically generated plastic waste, countries should consider separate targets for imported plastic waste, recognizing their distinct characteristics.

Our research indicates that while the average *RRR* of 63% is higher than the domestic average of 23% across 22 research countries, it still falls short of ideal recycling rates. This gap suggests a significant portion of traded plastics may be mismanaged(Sarira et al., 2022). To address this, transparent tracking systems, such as a robust Prior Informed Consent procedure(Basel Convention, 2019), are essential. The OECD control system for waste recovery serves as a notable example, requiring disclosure of pre-consented recovery facilities and technologies in waste-importing countries(OECD, 2021). Although recycling costs may be higher in developed countries, the overall environmental impact is often lower compared to that in Southeast Asia. These environmental concerns are reflected in the EU's newly adopted waste shipment regulation, which bans plastic waste exports to non-OECD countries starting in November 2026(European Commission, 2024).

Our approach to calculating the *RRR* focuses on primary cost factors, providing a minimum benchmark for recycling imported plastic waste. The actual *RRR* might be higher when considering additional costs like environmental impact, capital investment, and operational expenses (e.g., chemical feedstocks(Larrain et al., 2021), maintenance(Nikiema & Asiedu, 2022), and value-added taxes(Uekert et al., 2023)). Although limited cost factors may underestimate the *RRR*, this method aligns with our goal of establishing a minimum benchmark, providing a better calibration than the domestic recycling rates previously used for imported plastic waste. Future research should explore the full costs and benefits of imported plastic waste for a more comprehensive *RRR* assessment.

Due to data constraints, we used primary plastic exports as a proxy for recycled plastic revenue to ensure consistency. However, advancements in recycling technologies (e.g., chemical, enzymatic, and solvent-based methods) may create higher-value products not captured by current primary plastic classifications(Mangold & von Vacano, 2022; Zhang et al., 2023), potentially leading to an overestimation of the *RRR* in some developed countries. Additionally, the four HS codes under 3915 may not fully reflect the quality and diversity of plastic waste, indicating a need for expanded classification coverage.

While our work provides valuable insights into country-specific recycling rates, it does not address regional disparities within countries. Variations in costs such as electricity, labour, and rent can be significant within a country, underscoring the need for future research to determine *RRR* at regional and city levels for more localized policymaking. Caution is also advised when applying the *RRR* to estimate recycled volumes and environmental impacts in trade transit countries or regions like Hong Kong (China), as inaccurate trade data may lead to errors in the *RRR* calculation. Prioritizing actual recycling rates determined through mass balance is recommended for precision, though the *RRR* remains useful for addressing data gaps and estimating rates where physical measurement is impractical.

3.4 Methods

3.4.1 Accessing the required recycling rate

Importers aim to profit from recycling plastic waste, but face uncertainty since the recyclability of the waste is often unknown until the container is opened(Stahel, 2019). They must balance maintaining a sufficient inflow of plastic waste for recycling while keeping costs below the market value of secondary plastics. This balance includes expenses such as waste import, labour, electricity, rent, and physical losses during recycling. We link the recycling rate of imported plastic waste to a cost-benefit inequation (Eqs 3.1-3.3) spanning 2013 to 2022. For each year within this period, we selected importing countries that accounted for 70% of the global plastic waste imports, resulting in a total of 22 research countries. This equation can be enhanced with regional data on costs, providing a more accurate reflection of *RRR* across geographical units.

$$\left(\sum_{p} W_{i,p,c,t} \times PI_{i,p,c,t}\right) + C_{i,c,t} \leq \left(\sum_{p} W_{i,p,c,t}\right) \times (1 - Q_i) \times R_{i,c,t} \times PR_{i,c,t} \qquad (3.1)$$

$$C_{i,c,t} = LAB_{c,t} + ELE_{i,c,t} + RET_{c,t} \qquad (3.2)$$

$$R_{i,c,t} \geq \frac{PI_{i,c,t} + c_{i,c,t}}{(1 - Q_i) \times PR_{i,c,t}} \qquad (3.3)$$

Where $W_{i,p,c,t}$ indicates the net weight of the imported plastic waste of type i (referring to one of four waste plastics documented in the harmonized system (HS): PE, PS, PVC, and others) from the country p to the country c of the year t ; $PI_{i,c,t}$ indicates the per-unit price of the imported plastic waste of type i by country c in the year t; The upper-case $C_{i,c,t}$ denotes the operational costs during the mechanical recycling of plastic waste i in the importing country c of the year t, including costs for labour ($LAB_{c,t}$), electricity ($ELE_{i,c,t}$), and rent ($RET_{c,t}$) in Eq. 3.2. Q_i indicates the physical loss of plastic waste of type i during mechanical recycling. $R_{i,c,t}$ indicates the recycling rate of imported plastic waste of type i in the country c of the year t; $PR_{i,c,t}$ indicates the per-unit price of recycled plastic of type i in the importing country c of the year t. The lower-case $c_{i,c,t}$ denotes the per-unit operational cost when dividing the $C_{i,c,t}$ by $\sum_p W_{i,p,c,t}$.

The minimum recycling rate of imported plastic waste, enabling an economic break-even point, is referred to as the *Required Recycling Rate* (*RRR*). To derive a consistent unit price of recycled plastics, we used the trade data for plastics in primary forms (i.e. plastic pellets, flakes, etc.) recorded in the UN Comtrade database from 2013 to 2022(UN Comtrade, 2024), which consists of both virgin and secondary plastics. Within the same database, we also accessed the trade data for plastic waste. Both unit prices for plastic waste and primary plastics are determined by dividing the trade values and the net weights between trading countries. Moreover, given that primary plastic includes a broader range of polymer subcategories than the four plastic wastes (waste PE, PS, PVC, and others), we further map waste PE with the primary plastics HDPE and LDPE, using a share factor that varies by country (Supplementary Table B6). Similarly, the 'others' waste category is mapped to primary plastics PET and PP. The unit price of imported plastic waste and primary plastic are calculated as follows:

$$PI_{i,c,t} = \frac{\sum_p V_{i,p,c,t}}{\sum_p W_{i,p,c,t}} \tag{4}$$

$$PR_{i,c,t} = \begin{cases} \dfrac{\sum_p V_{PS,p,c,t}}{\sum_p W_{PS,p,c,t}} \left(or \ \dfrac{\sum_p V_{PVC,p,c,t}}{\sum_p W_{PVC,p,c,t}} \right) & \text{if } i \text{ is PS } (or \text{ PVC}) \\ \dfrac{\sum_p V_{LDPE,p,c,t}}{\sum_p W_{LDPE,p,c,t}} \times r_{LDPE,c} + \dfrac{\sum_p V_{HDPE,p,c,t}}{\sum_p W_{HDPE,p,c,t}} \times r_{HDPE,c} & \text{if } i \text{ is PE} \\ \dfrac{\sum_p V_{PET,p,c,t}}{\sum_p W_{PET,p,c,t}} \times r_{PET,c} + \dfrac{\sum_p V_{PP,p,c,t}}{\sum_p W_{PP,p,c,t}} \times r_{PP,c} & \text{if } i \text{ is Others} \end{cases} \tag{5}$$

Where $V_{i,p,c,t}$ and $W_{i,p,c,t}$ indicate the trade value and net weight of imported plastic waste of type i from the country p to country c in the year t; $V_{ps,p,c,t}$ and $W_{ps,p,c,t}$ (also subscripts for PVC, HDPE, LDPE, PET, and PP) indicate the trade value and net weight of six types of primary plastic exported from country c to country p in the year t, respectively. By combining HDPE and LDPE as PE, PET and PP as 'others' with the share factors of $r_{HDPE,c}$, $r_{LDPE,c}$, $r_{PET,c}$, and $r_{PP,c}$ in the country c, six primary plastics are mapped to four plastic waste types.

3.4.2 Processing bilateral trade data

We analysed 186,861 bilateral trade entries of plastic waste and primary plastic reported from both 22 research countries and their trading partners from 2013 to 2022 in the UN Comtrade database. These entries include trade value and net weight for four plastic waste types (waste PE: 391510; waste PS: 391520; waste PVC: 391530; waste others: 391530) and six primary plastic types (HDPE: 390110; LDPE: 391520; Expandable PS: 390311; PVC: 391530; PET: 390760; PP: 390210).

Each trade entry typically includes details such as reporting country, partner country, period, net weight, and trade value. Ideally, each trade flow should be reported by both importer and exporter during the same period, with closely aligned net weight and trade values. However, discrepancies often arise due to varying reporting conventions; exporters typically report trade values as Free On Board (FOB), while importers report them on a Cost for Insurance and Freight

(CIF) basis. For our analysis, we require trade values for a country's imported plastic waste and its exported primary plastics. There are two options: using trade values reported by the research country, including plastic waste import (CIF basis) and primary plastics export (FOB basis), or using mirror trade values reported by the trading partner of the research country, including plastic waste export (FOB basis) and primary plastic import (CIF basis). In calculating the *RRR* via the cost-benefit equation, we aim to incorporate the international transport cost for importing plastic waste while excluding the transport revenue for recycled primary plastics. Therefore, we prioritize using plastic waste imports (CIF basis) and primary plastics exports (FOB basis), both reported by the research countries. However, for a robustness check, we also include results based on mirror trade data reported by the trading partners of the 22 research countries in Supplementary Table B1.

We detected trade value outliers through a distributional analysis of the value-to-mass ratio for all trade entries of specific plastic types each year(Brewer et al., 2020; Chen, Jiang, Li, Wang, Wang, Zhang, Zhang, Ma, Huang, & Lu, 2022; Szkutnik, 2020). Since most of these unit price distributions follow a lognormal pattern, we transformed them into normal distributions by taking the natural logarithm (ln($/kg))(Chatham House, 2024). By identifying outliers greater than three standard deviations from the mean value, approximately 2.4% and 2.6% of plastic waste and primary plastic trade entries were flagged as outliers, respectively.

After grouping the trade values by research countries, period, and plastic types, empty trade values were replaced with mirror data if available. For example, if trade values for China's waste PVC import in 2022 were reported as empty, trade values reported by its trading partners as exports in 2022 would be retrieved if available. This replacement accounted for 2.6% and 2.5% of grouped plastic waste and primary plastic entries, respectively. Further details regarding the stepwise changes in trade entries when processing the original trade data are provided in Supplementary Table B7 for both plastic waste and primary plastic trades reported by both research countries and their trading partners.

3.4.3 Costs and physical loss

The complete costs from importing plastic waste to producing recycled plastics include plastic waste imports, operational costs (electricity, labour, land rent, water, fuel, transportation, maintenance), fixed asset investments (buildings, machinery, equipment), potential environmental costs, and taxes(Faraca et al., 2019; Larrain et al., 2021; Uekert et al., 2023). Based on the work of Uekert et al., Larrain et al., and Faraca et al.(Faraca et al., 2019; Larrain et al., 2021; Uekert et al., 2023), we consider the four costs consistently across research countries from 2013 to 2022: imports (as indicated by the UN Comtrade database), electricity, labour, and rent.

The labour cost for recycling 1 kg of plastic waste was calculated by multiplying the labour input intensity (the required person-hours to recycle one kilogram of plastic waste) by the hourly earnings of employees in each country. The labour input intensity was determined by the recycling company's annual output and its number of employees, sourced from voluntary disclosures on independent recycling company websites and reports by industry associations, as presented in Supplementary Table B8. The production rate (expressed in kg/person-hours) was derived by dividing the company's annual recycling output by the number of its employees and the yearly working hours, which are standardized as 8 hours a day and 365 days a year. Subsequently, the labour input intensity was obtained by taking the inverse of the production rate, and these values are averaged at the country level (see Supplementary Table B8). The hourly earnings of employees (by manufacturing industry) during 2013-2022 across countries were referenced from the statistics on ‘Average monthly earnings of employees by sex and economic activity (annual)’ by the International Labour Organization(International Labour Organization), as shown in Supplementary Table B9.

The electricity cost for recycling per-unit plastic waste is derived by multiplying per-unit electricity consumption varied by plastic wastes and the industrial electricity price across countries and years. We sourced the electricity consumption per plastic waste in mechanical recycling from Life cycle inventories (Ecoinvent and LCA Commons) and other literature (detailed in Supplementary Table B10). For European countries, the industrial electricity tariffs were obtained from Eurostat (see Supplementary Table B11)(Eurostat). For other countries, the tariffs were gathered from governmental documents or power company announcements, as shown in Supplementary Table B12.

The rent for recycling 1 kg of plastic waste is based on the area required to recycle 1 kg of plastic waste per year (m^2/kg*yr), which is calculated by dividing the land area occupied by a recycling company (plants are included) by its annual recycling output (see Supplementary Table B13). This value is subsequently multiplied by the annual industrial rent across countries and years, primarily sourced from either yearly or quarterly reports of real estate companies (see Supplementary Table B14). The physical losses of four plastic wastes during mechanical recycling stem from prior literature (see Supplementary Table B15), where the input of plastic waste and the output of recycled plastic are collected.

3.4.4 Sensitivity and uncertainty analyses

A one-at-a-time sensitivity analysis was conducted to determine how the alteration of key variables impacts the *RRR*. The six key variables include four costs (imports, labour, electricity, and rent), product price, and physical loss during the mechanical recycling process. Two values (the minimum and maximum value) presenting the pessimistic and optimistic cases for each variable were selected in a 10-year series (2013-2022) across countries.

The probability range of the *RRR* was studied with a Monte Carlo simulation, where all six variables are included. Referring to Larrain et al. (2021)(Larrain et al., 2021), the product price of recycled plastic is modelled by the normal distribution, with the value of mean and standard deviation evaluated from the 10-year time series across countries. The costs for labour, electricity, rent, and physical loss during the recycling process are assumed to have a Pert distribution, with the minimum value, maximum value, and the most likely value (median value) selected across countries. The import cost is considered to fit a modified Pert distribution with a most likely value weight equivalent to the minimum and maximum value(Keefer & Verdini, 1993). The resulting uncertainties are propagated with a Monte Carlo simulation (sampling of 30000) using kernel density smoothing(Wand & Jones, 1994).

3.5 Data and code availability

The required recycling rate data by country, year, and plastic waste type generated in this study have been deposited under Zenodo (https://doi.org/10.5281/zenodo.8328894), along with other supporting data. In case of questions or requests, please contact K.L.