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Global Polyethylene Terephthalate (PET) Plastic Supply Chain Resource Metabolism Efficiency and Carbon Emissions Co-Reduction Strategies

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Abstract: Polyethylene terephthalate (PET) is widely used as a primary plastic packaging material in the global socio-economic system. However, research on the metabolic characteristics of the PET industry across different countries, particularly regarding the entire life cycle supply chain of PET, remains insufficient, significantly hindering progress in addressing plastic pollution worldwide. This study employs the Life Cycle Assessment-Material Flow Analysis (LCA-MFA) method to comprehensively analyze the environmental impacts of PET plastics, with a focus on the processes from production to disposal in 12 regions (covering 41 countries) in 2020. By constructing 13 scenarios and analyzing the development trajectory of PET plastics from 2020 to 2030, this study provides scientific evidence and specific strategies for waste reduction and emission reduction measures in the PET industry. Overall, in 2020, the 12 regions (41 countries) consumed 7297.7 kilotons (kt) of virgin PET resin and 1189.4 kt of recycled PET resin; 23% of plastic waste was manufactured into recycled PET materials, 42% went to landfills, and 35% was incinerated. In 2020, the entire PET plastic supply chain emitted approximately 534.6 million tons (Mt) of carbon dioxide equivalent per year, with production emissions accounting for 46.1%, manufacturing stage emissions accounting for 44.7%, and waste treatment stage emissions accounting for 9.2%. Research indicates that under a scenario of controlled demand, resource efficiency improvement and emission reduction are the most effective, potentially reducing carbon emissions by up to 40%.

Keywords: material flow analysis (MFA); life cycle assessment (LCA); polyethylene terephthalate (PET); plastic; carbon emissions

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1. Introduction

Plastic has become an indispensable part of human life [1], mainly composed of petrochemical fuels [2], with an annual production reaching as high as 300 billion tons. Polyethylene terephthalate (PET) has emerged as a cornerstone of the modern plastics industry due to its versatility and mechanical strength. Predominantly utilized in packaging, notably for beverage bottles, and in the textile industry as a fiber material, PET's application has seen a multifold increase in the past few decades [3–5]. Despite its widespread use, the environmental sustainability of PET remains a critical concern. Non-biodegradability and issues related to the end-of-life disposal of PET products have catalyzed significant environmental challenges, spotlighting the urgent need for effective recycling strategies [6]. The plastic industry also contributes significantly to greenhouse gas emissions, with over 90% of plastics being produced from petroleum-based materials, accounting for 20% of total petroleum consumption. To mitigate the environmental impact of PET plastic, it is

essential to understand the flow of information regarding the production, manufacturing, use, recycling, and end of life of plastics.

Currently, the flow of plastics at the national, regional, and even global level is drawing attention. At the global level, Geyer et al. (2017) quantified the production, use, and waste of plastics from 1950 to 2015 using dynamic Material Flow Analysis [2]. Ryberg et al. (2019) specifically quantified the losses at various stages of the life cycle of plastics globally in 2015 using a static Material Flow Analysis approach [7]. At the regional level, Ciacci et al. (2017) focused on analyzing the material consumption and societal stock changes in European PVC plastics during the use phase from 1960 to 2012 [8]. Kawecki et al. (2018) quantified the flow of seven types of plastic commodities in European society [9]. Luan Xiaoyu et al. (2020) constructed a dynamic Material Flow Analysis model for plastics in China from 1949 to 2018 [10]. Van Eygen et al. (2017) used a static Material Flow Analysis method to establish a quantitative model of plastic production, consumption, and waste in Austria in 2010 [11]. Jang et al. (2020) constructed a metabolism model for South Korean plastic packaging in 2017 [12]. Bureecam et al. (2018) studied the flow and stock of plastics in Thailand in 2013 using Material Flow Analysis, aiming to provide recommendations for Thailand's waste management policy [13]. However, these studies are usually conducted at the level of individual countries or regions, with few comparative analyses across multiple countries, and there is a scarcity of research covering the entire supply chain of the PET plastic industry. They rarely quantify considerations of the secondary materials market (R-PET saturation issues), the import and export of plastic waste, and the differences between closed-loop and open-loop recycling. And there is a lack of information about the end-use market for recycled resins. These significantly hamper the development of the circular economy and the improvement in resource metabolism efficiency in various countries.

The Life Cycle Assessment (LCA) has previously been applied to assess the environmental impacts of plastic resins during the production stage, including PET [14] and PP [15], among others. However, most studies typically focus on analyzing the impacts during the resin production stage or across the entire life cycle of specific plastic products., such as PVC window frames [16], PP masks [17], and PE bottles. Beyond primary production, emissions from synthetic resins can occur at every stage of their life cycle, including manufacturing, use, and disposal [18]. Greenhouse gas emissions associated with the plastic life cycle at various stages of the material supply chain have not yet received adequate attention. In summary, integrating the material flows and environmental impacts at each stage of the plastic life cycle will further monitor greenhouse gas emissions on a broader systemic scale [19].

Here, this study combines Life Cycle Environmental Impact Analysis (LCA) with the Material Flow Analysis (MFA) model to measure the multi-life-cycle environmental impacts of the PET plastic supply chain, thereby providing valuable insights for promoting the sustainability of plastics. Unlike previous studies, we established the latest framework for PET plastic material flow and conducted a comprehensive analysis of the PET plastic value chain in 2020 across 12 global regions (41 countries), whose PET production accounts for over 95% of the global total. Moreover, in the MFA, we quantitatively consider the secondary materials market (R-PET saturation issues), the import and export of plastic waste, and the information on the end-use market for recycled resins. We use a dynamic modeling approach, policy-oriented, to construct 13 scenarios (regarding plastic waste disposal, demand growth, import and export trade and, open-loop and closed-loop recycling), analyzing the trajectory of PET plastic from 2020 to 2030. The main objectives of this study include the following:

1. Establishing the material flow baseline for the PET plastic supply chain in 2020 for major producing countries, divided into 12 regions (41 countries in total), and assessing the PET resource metabolism efficiency of each country;
2. Calculating the annual greenhouse gas emissions of the PET supply chain in 12 countries and regions (covering 41 countries) in 2020, identifying emission hotspots;

3. Assessing the potential for improving resource metabolism efficiency and the potential for reducing greenhouse gas emissions in the PET plastic industry under 13 scenarios from 2020 to 2030 (related to plastic demand, plastic waste exports, waste collection, and recycling technologies), providing scientific support for strategies aimed at reducing plastic waste generation and greenhouse gas emissions.

2. Materials and Methods

2.1. System Boundaries

This article covers 41 countries (divided into 12 countries and regions), treating Europe as a single entity for this study. These are Europe (EU27+3 countries: UK, Norway, and Switzerland), China (excluding Hong Kong, Macau, and Taiwan), Japan, South Korea, Thailand, Australia, India, Brazil, South Africa, Mexico, Indonesia, and the United States. For detailed information on the specific countries, their codes, and abbreviations, please refer to Table S1.

Figure 1 shows the system boundaries of PET plastic, including the processes of PET production, manufacturing, use, waste disposal, and recycling. The PET production phase mainly involves the production of amorphous and bottle-grade PET resins. Considering that currently, bio-based plastics account for less than 0.1% of the total plastic consumption [20,21], only petrochemical PET resin is considered. PET manufacturing primarily refers to the process of producing PET products from PET resin through techniques such as stretch blow moulding, extrusion, and polyester fibre production. PET products are mainly manufactured into four categories: PET bottles, films, fibers, and other products containing PET. Due to the wide range of processes and their relatively small quantity share, which exceed 600 types [22], the "other" category in the manufacturing process is not well-defined. During the manufacturing of PET products, some of the material is lost and enters recycling, while the rest moves on to the usage stage. Since the lifespan of PET products often does not exceed one year [23], we assume that PET plastics exit the system within a year. The waste disposal phase primarily includes the collection, sorting, recycling, incineration, and landfilling of PET waste. The recycling of PET waste includes mechanical recycling and chemical recycling. Mechanical recycling, which is less costly, is the method most commonly used for PET recycling [23,24], while chemical recycling is more expensive and requires higher standards [25]. Currently, most polyester is mechanically recycled from PET, and the market share of chemically recycled polyester is less than 1%. Therefore, this article only considers mechanical recycling [21,26]. The above describes the flow of PET within a specific region or country. In addition, we have also considered trade, including the trade of PET resin, PET products, and PET waste. Trade-related information can be found in Table S2.8.

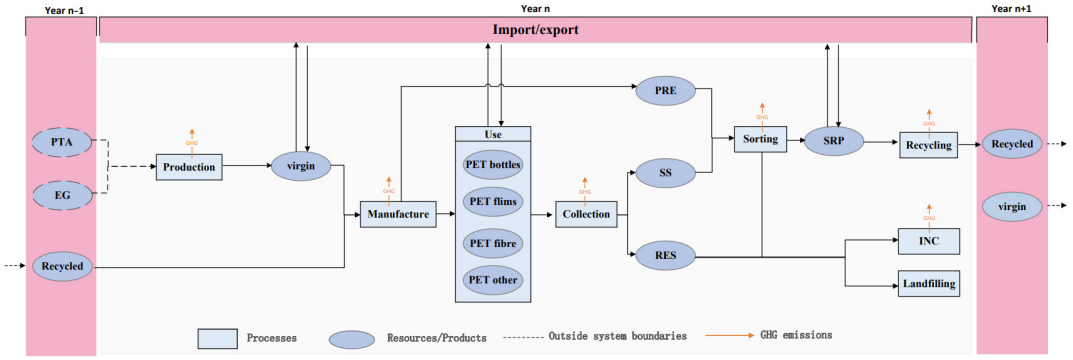


Figure 1. System boundary diagram, taking a country as an example, shows how flows are connected across different years. INC: incineration, PRE: pre-cosumer, RES: residual waste, SS: source-separated waste, PTA: pure terephthalic acid, EG: ethylene glycol.

The main scope of Life Cycle Assessment (LCA) includes the production of PET resin, the manufacturing of PET products, and end-of-life disposal and recycling. The greenhouse gas emissions from PET resin production include all activities from cradle to the gate of the PET production plant. The emissions from PET manufacturing primarily refer to the process of producing PET products from PET resin through techniques such as stretch blow molding, extrusion, and polyester fiber production. Waste management refers to the sorting, recycling, incineration, and landfilling of PET products [27]. During the landfilling process, considering that PET plastics are not easily degradable, it is assumed that no greenhouse gas emissions are produced [28]. We calculate the emissions from incineration based on the combustion factors of PET plastics and take into account the electricity recovery from incineration. The efficiency of incineration by country can be found in Table S2.7. Due to the lack of official transportation data in various countries, there is a large discrepancy in transportation distances for the same country reported in different studies. For example, transportation data in Europe ranges from 50 to 4000 km, which generates considerable uncertainty [29–35]. Moreover, related studies show that the emissions of plastic from their transportation account for less than 5% of their total life cycle; therefore, this study does not consider emissions from transportation [36].

2.2. Modeling Approach

The modeling process of material flows mainly consists of three steps, and the model framework mainly draws on the material flow model framework developed by Marie Kampmann Eriksen [19] in 2020. However, within the material flow model framework established, we further connect with the Life Cycle Assessment method to calculate greenhouse gas emissions.

Firstly, based on the MFA method provided by Brunner and Rechberger, both static and dynamic MFA models were developed and coordinated in Excel 2021 [37]. Based on the existing data of PET flows in 12 regions (41 countries) for the year 2020, a static Material Flow Analysis (MFA) model was established. By dividing the mass output of a process by its mass input, the Transfer Coefficients (TC) were determined, which describe the division of mass inputs and outputs for each process within the system.

Secondly, a dynamic MFA model was constructed to represent the baseline scenario, which includes data on the plastic demand growth rate, recycling pathways, and the Transfer Coefficients (TC) derived from step 1. The recycled materials in the first year are input into the second year, and we calculate the required virgin material consumption (*VMC*) for the second year. The calculation formula is given by Equation (1):

$$VMC_{n+1} = C_{n+1} - R_n, \quad (1)$$

C_{n+1} is the expected consumption in year $n + 1$, calculated by applying annual growth rates to the plastic demand from 2020. Due to recycling, the quality of recycled plastics may be reduced [38,39]. The maximum content of recycled plastic was defined for each product group (RC^{max}), to ensure the quality and functionality of the products.

$$R_n \leq C_{n+1} \times RC^{max}, \quad (2)$$

All scenarios are calculated with $RC_{max} = 1$. For PET, Welle [40] states that it is technically possible to use 100% recycled PET in bottles as well as film. In some companies such as MOSCA [41] also use 100% recycled PET in manufacturing. In situations where $R_n > C_{n+1} \cdot RC^{max}$, meaning the recycled plastics market is saturated, it is assumed that the "surplus" recycled plastics are lost (end up in landfill), thus they can neither substitute virgin plastics nor contribute to the recycling rate (*RR*).

Thirdly, we established 13 scenarios representing potential measures for the PET plastic cycle and adjusted the Transfer Coefficients (TC) for each process. Each scenario represents a dynamic Material Flow Analysis (MFA). Our aim is to provide useful insights into the system's behavior rather than to predict the future.

Finally, by combining MFA and LCA, we calculate the greenhouse gas emissions for each life cycle stage of PET plastics, the formula is given by Equation (3):

$$GHG^y = \sum_1^k Q_k^y \times E_{i,k}^y, \quad (3)$$

GHG^y represents the GHG emissions during PET life cycle in y years, Q_k^y represents the annual production or amount of PET in the life cycle stage k in y years (quantified using MFA), $E_{i,k}^y$ represents the amounts of GHG. i represents the GHG emitted per unit mass of PET in y years in the life cycle stage k (quantified using LCA) [42]. i refers to different types of GHG, such as carbon dioxide, methane, and nitrous oxide; k shows the life cycle stage, i.e., PET production, manufacturing, and waste management stages; y shows the year between 2020 and 2030.

2.3. Scenario Definition

We modeled and compared the BAU with seven different future waste management alternatives and six comprehensive scenarios that include demand growth.

2.3.1. Baseline Scenario (S0)

Baseline scenario (S0): The baseline involves production data, waste management levels, and recycling pathways, as well as annual growth rates for PET demand in various countries for the year 2020. All input data are provided in Tables S2.1–S2.9.

2.3.2. Improvement in Collection (S1)

For the recycling of bottles and films, we refer to the circular economy targets set by various countries, with specific details available in Table S3.1.

Among discarded PET products, the recycling and reuse of PET fiber textiles are the most challenging due to the presence of many impurities, dyes, moisture content, and gel particles [43,44]. The recycling rate of PET fibers is only 14.40%. Since PET fibers are considered low-quality recyclable materials, a significant development of chemical recycling processes for PET fibers is necessary for substantial recycling. However, current chemical research on this is mostly at the laboratory stage; there is still some distance from practical application. Therefore, we assume that the recycling rate of fibers will not change from 2020 to 2030.

2.3.3. Improvement in Sorting (S2)

Long-term studies on various plastic recyclers have shown that sorting efficiency at these facilities increases by 1% each year [45]. This finding has been adopted as an assumption for our analysis, with detailed information available in Table S3.2.

2.3.4. Improvement in Recycling (S3)

Long-term studies on various plastic recyclers have shown that recycling efficiency at these facilities increases by 0.5% [45]. Consequently, we have incorporated this finding into our assumptions, with detailed information available in Table S3.3.

2.3.5. Improvement in Incineration with Energy Recovery (S4)

As countries increasingly focus on the resource utilization of plastic waste and reducing waste, the amount of landfilling will decrease. EU member states are set to comply with a landfill limit of 10% by 2035, with a consistent annual reduction in landfill quantities [46]. China's "14th Five-Year Plan" aims for a 60% resource utilization rate of urban household waste by the end of 2025, reaching 80% by 2030 [47]. We assume landfill and incineration rates based on the policies of various countries. For developed countries without specific policy directives, we assume that by 2050 they will achieve 100% resource utilization with a landfill rate of 0, with linear growth in the intervening years. For developing countries like India, where infrastructure is lacking and a significant amount of plastic waste is

not properly managed, we assume that by 2030, 50% of plastic waste will be properly handled and the incineration rate will reach 30% [48], with detailed information available in Table S3.4.

2.3.6. Banning the Export of Waste (S5)

In recent years, various countries have introduced policies related to the import and export of plastic waste. On 19 January 2020, China's National Development and Reform Commission and the Ministry of Ecology and Environment issued a new plastic restriction order "Opinions on Further Strengthening the Control of Plastic Pollution" which completely bans the import of waste plastics. The Thai cabinet has decided to ban all imports of plastic waste from 1 January 2025. India's Ministry of Environment, Forest and Climate Change announced in 2019 a total ban on the import of solid plastic waste. The trend is for countries to manage plastic waste internally rather than through import and export trade. Therefore, we assume that by 2030, all countries will cease the trade of waste plastics.

2.3.7. Committing 100% to Strict Closed-Loop (S6)

Increasingly, more manufacturers and various national PET bottle associations are committing to develop closed-loop recycling [49,50]. This means bottles are recycled back into bottles, fibers back into fibers, and films back into films. If the secondary recycling market becomes saturated, it is assumed that surplus materials will be landfilled.

2.3.8. Recycling 100% to Fibers (S7)

Recycling 100% into fibers indicates a situation where the PET packaging market is overwhelmed with cheap raw materials, making the polyester sector the sole destination market. When the demand for recycled PET fills the capacity of the polyester market, excess PET recycled materials will end up in landfills.

Below, we have established six comprehensive scenarios, taking into consideration the growth in PET demand.

2.3.9. Combined Scenarios (S8–S13)

This paper establishes six integrated scenarios to reflect the metabolism of PET resources and carbon emissions under various combined scenarios, as shown in Table 1.

Table 1. Combined scenarios.

Scenario	Combination Methods	Plastic Demand
S8	S1–S5	increasing by growth rate
S9	S1–S5	zero growth rate, demand maintained at 2020 level
S10	S1–S5 + S6	increasing by growth rate
S11	S1–S5 + S6	zero growth rate, demand maintained at 2020 level
S12	S1–S5 + S7	increasing by growth rate
S13	S1–S5 + S7	zero growth rate, demand maintained at 2020 level

2.4. Evaluation Indicators

This article selects four indicators, as shown in Table 2. The recycling rate (*RR*) is an official indicator for many countries [46], defined as the weight of waste entering recycling facilities divided by the total amount of waste generated, representing the percentage of plastic waste effectively recycled. The Circular Material Use Rate (*CMUR*) is also an official indicator in some countries, such as the European Union, indicating the percentage of recycled plastic in the total plastic demand. The Closed-Loop Circulation Rate (*CLCR*) is an improved version of the circular potential developed by Eriksen, that illustrates the system's ability to close material loops while maintaining material quality. The indicators *RR*, *CMUR*, and *CLCR* represent the degree of recycling in various countries. The *VMC*

indicator reflects the absolute amount of virgin plastic required to meet the annual total demand, aligning with the goal of the circular economy to reduce quantities.

Table 2. Equations for calculating circulating metabolic indicators.

Type	Indicator	Formula
Recyclability	*RR* (%)	$RR_n = \frac{R_n}{W_n^{tot}} \times 100\%$
	CMUR (%)	$CMUR_n = \frac{R_{n-1}}{C_n} \times 100\%$
	CLCR (%)	$CLCR_n = \frac{R_n^{same}}{C_n} \times 100\%$
Demand for virgin resin	*VMC* (kt)	$VMC = C_n - R_{n-1}^{rec}$

R: the total amount of plastics that were successfully recycled in year n or $n-1$, excluding any excess that occurred due to market saturation (see Section 2.2 on exports). It also excludes plastics that were possibly recycled outside the study's boundaries. R_n^{same}: the volume of recycled plastics that was processed back into the same type of products as originally manufactured in year n, C_n: total consumption of plastic in year n, W_n^{tot}: total quantity of waste generated in year n, including waste that is exported. These figures are all presented in kilotons (kt) on a mass basis.

2.5. Data Source

The material flow data for PET plastics mainly come from statistical databases of various countries, reports from PET associations, and the published literature. For detailed information, refer to Tables S2.1–S2.9. The data for LCA come from the related literature, national reports, and life cycle databases (such as ELCD, CLCD, Ecoinvent, Korea LCI database, and USLCI) [51–56]. For detailed information, refer to Table S4. For some countries, such as India and Indonesia, due to the lack of life cycle data, this study coordinates on the basis of global data, adjusting with the electricity and heat factors specific to each country. Given the availability of data, we have also performed an uncertainty analysis, which can be found in Table S5.

3. Results

3.1. Baseline Material Flow System of PET

Using material flow methods, this study characterized the flow of PET plastics in various countries. The overall flow of PET plastic in various countries in 2020 is shown in Figure 2.

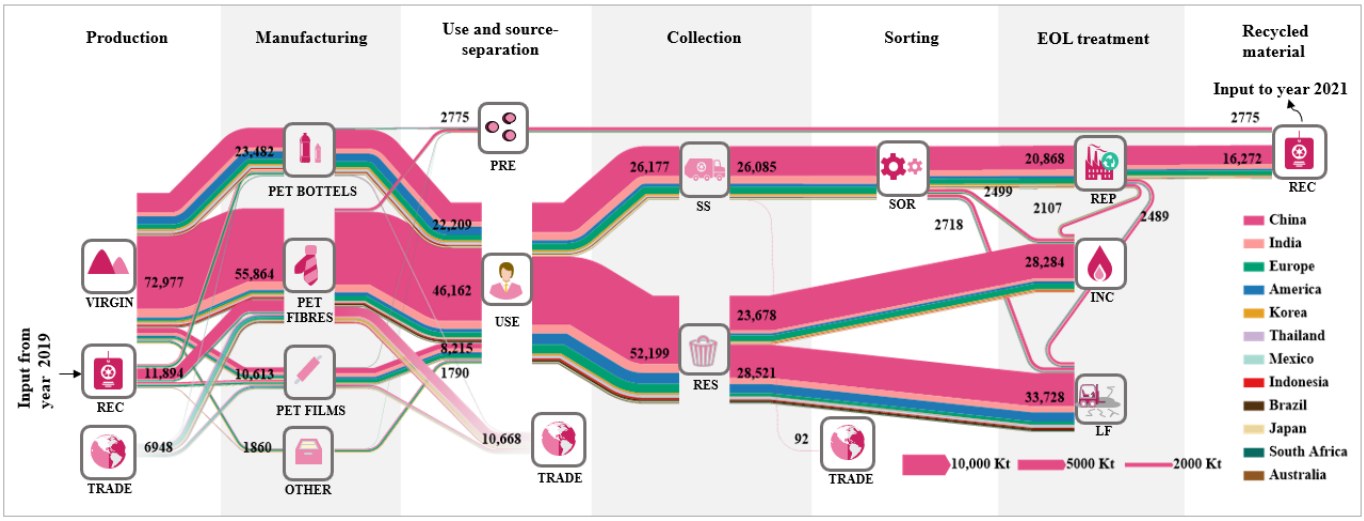


Figure 2. Baseline material flow system for PET (2020). Note: The width of the arrows is proportional to the size of the material flow. Trade flows (imports and exports) are represented by a color gradient, from light to dark. INC: incineration, LF: landfill, PRE: preconsumer, REP: reprocessing, RES: residual waste, and SS: source-separated waste.

Overall, the 12 regions consumed 72,977 kt of virgin PET resin and 11,894 kt of recycled PET resin. China's production of PET resin in 2020 reached 49,480 kt, accounting for 66% of the total output, making it a leading producer of resin [6,43]. In consumption, the product proportions are as follows: PET fibers (61%), PET bottles (25.5%), PET films (11.5%), and other PET products (2%). Fibers occupy the majority of the PET market [57]. Imports amounted to 6948 kt, and exports were 10,668 kt. This is because the import and export data are derived from a global trade database, and the study area covers only 41 countries, leading to measurable import and export volumes. As for the final destination of PET plastics, 23% of plastic waste is turned into recycled PET materials, 42% ends up in landfills, and 35% of the plastics are incinerated. The recycling level in the PET plastic industry is higher than that of the global plastic industry, with a recycling rate of only 9% [58]. This is because PET bottles are easier to recycle compared to other types of plastics, and many countries have established comprehensive waste collection systems for PET bottles. Additionally, some countries, such as the United States, Europe, and Australia, have implemented PET bottle deposit return schemes [59,60]. However, recycling fibers in the PET industry is difficult [20], greatly limiting the development of recycling in the PET sector. Although fibers can be recycled chemically, the global share of chemical recycling is low, and it is economically expensive and consumes a lot of energy [23,61]. The production, manufacturing, consumption, and disposal of PET plastics are predominantly concentrated in four major countries: China, India, the United States, and Europe. These four nations accounted for over 85% of global PET plastic production, consumption, and disposal in 2020. These countries should be identified as focal points for reducing PET plastic usage. When formulating management measures for PET plastics, it is imperative to adopt a systemic approach that encompasses the entire life cycle process of PET plastics rather than focusing solely on specific stages.

The United Nations Comtrade Database, created by the United Nations Statistics Division, is the largest and most authoritative international commodity trade database globally [62]. We conducted a thorough screening and review based on the classifications of plastics in the United Nations Commodity Database. There are 58 commodities related to PET, divided into PET resin, PET bottles, PET films, PET fibers, and PET waste, with specific codes and details provided in Table S2.8. Figures 3 and 4 display the total trade volume and trade flows among countries, where China is the largest exporter, accounting for 60% of the global export volume, followed by South Korea, India, and Thailand. Together, these four countries make up 94% of the global export volume. Within the study region, Europe, the United States, Japan, and Brazil are the main importers, representing 50% of the total imports. The import and export activities occur not only within the countries of the study region but also extend to other countries outside the study area. In contrast, the trade volume of PET waste is relatively low, accounting for only 1.5%. Despite the significant attention given to the trade of plastic waste, the relatively small proportion of PET within the category of plastic waste results in a comparatively smaller trade volume.

From the perspective of import and export product types, these four products, PET fibers, PET resin, PET films, and PET bottles, together account for 98.5% of the total trade volume. Among these, PET fibers have the largest share at 44%, followed by PET resin at 36%, PET films at 15%, and PET bottles at 3.5%. Trade in PET waste is comparatively minor, making up just 1.5% of the total. Although the trade of waste plastics has received widespread attention, the proportion of PET types within waste plastics is relatively low. Table S2.9 details the percentages of different types of plastics in waste across various countries.

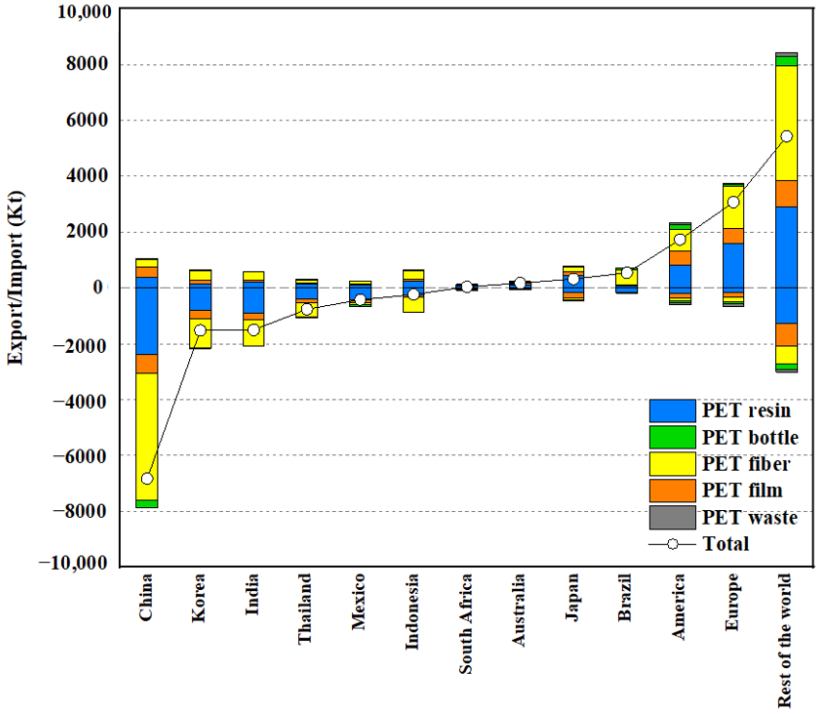


Figure 3. PET product imports and exports by country in 2020, in units of thousand metric tons (kt). It is arranged from left to right by net import amounts. We set import values as positive and export values as negative.

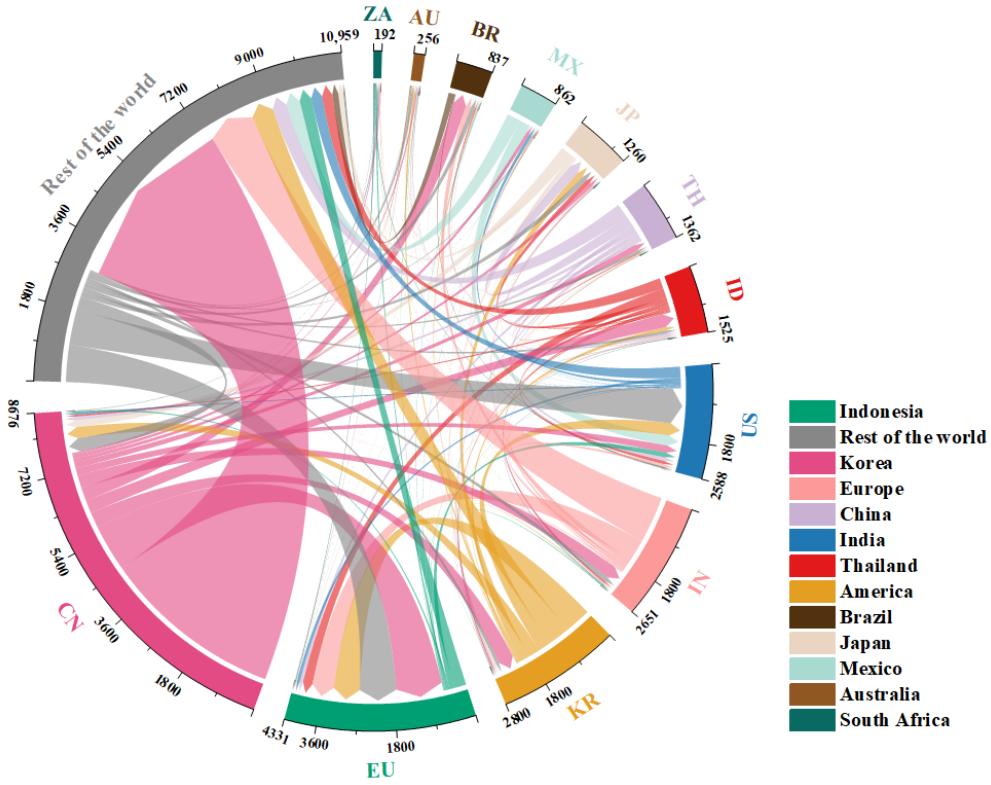
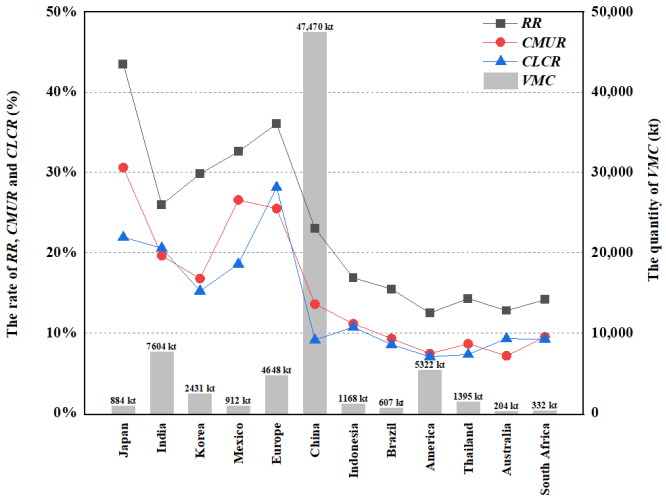


Figure 4. The trade flow of PET products among countries in 2020, in units of kilotons (kt). Countries or regions are abbreviated according to the ISO 3166-1 alpha-2 standard [63]. CN: China, EU: Europe, KR: Korea, IN: India, US: America, ID: Indonesia, TH: Thailand, JP: Japan, MX: Mexico, BR: Brazil, AU: Australia, ZA: South Africa.

3.2. Resource Metabolism Efficiency across Countries

The resource metabolic efficiency varied among different countries in 2020. Figure 5a depicts the status of resource metabolism efficiency in 2020, encompassing circularity and the utilization of virgin resin. Figure 5b illustrates the ranking of these indicators for each country. Japan, Europe, Mexico, South Korea, and India have notably higher recycling rates (*RR*), with 42.5%, 36.1%, 32.6%, 29.8%, and 26.0%, respectively, all exceeding 25%. China, Indonesia, and Brazil have moderate recycling rates ranging from 15% to 25%, while Thailand, South Africa, Australia, and the United States show lower recycling rates, falling under 15%. This demonstrates that these countries face challenges in PET plastic recycling and require increased policy support and investment to enhance circularity levels. It is worth noting that casual disposal after consumption is one of the primary reasons for the environmental threat posed by waste PET [64]. To reduce the pollution caused by plastic waste and minimize its environmental impact, it is imperative to reduce the production of plastic waste at its source [65,66]. Therefore, governments worldwide should strive to encourage green consumption among residents, enhance consumers' awareness of resource conservation and environmental protection, reduce the casual disposal of plastic waste, and further increase the collection rate of plastic waste, decrease landfill rates, and improve recycling and incineration rates.



(**a**)

	RR	*CMUR*	*CLCR*	*VMC*
Japan	1	1	2	9
Europe	2	3	1	4
Mexico	3	2	4	8
Korea	4	5	5	5
India	5	4	3	2
China	6	6	9	1
Indonesia	7	7	6	7
Brazil	8	9	10	10
Thailand	9	10	11	6
South Africa	10	8	8	11
Australia	11	12	7	12
America	12	11	12	3

(**b**)

Figure 5. (**a**) The *RR*, *CMUR*, *CLCR*, and *VMC* values for each country. (**b**) Ranking chart of *RR*, *CMUR*, *CLCR*, and *VMC* for each country.

Regarding the Circular Material Use Rate (*CMUR*), this metric shows the proportion of recycled materials in national or regional consumption. Except for Japan, which achieved 30.6%, all other countries fell below 30%, indicating insufficient use of recycled materials. Mexico is next at 26.6%, followed by Europe at 25.5%, aligning with the findings reported by Plastics Europe 2020 [67]. These data indicate that while some countries have made progress in the utilization of recycled plastics, the global utilization rate of recycled plastics remains relatively low. Japan has shown relatively good performance [68], but there is still room for improvement in other countries. Strengthening the utilization of recycled plastics is crucial for advancing the development of a circular economy [69], and countries should intensify efforts and adopt effective policies and measures to promote the widespread application of recycled plastics, thus achieving sustainable resource utilization and environmental protection.

For the Closed-Loop Circulation Rate (*CLCR*), Europe leads with 28.1%, indicating that although its recycling efficiency might not match other countries, it excels in ensuring recycled materials are not downgraded in the recycling process. India and Japan also

score above 20%. Despite India being a developing nation, it has a significant number of collectors and non-governmental recycling entities that gather PET bottles and other recyclable plastics to generate income [70,71]. The *CLCR* in other countries is not high, all falling below 20%.

The *VMC* indicator is an important measure of the original plastic usage situation, helping identify countries where significant efforts are needed to control and reduce plastic consumption. Based on the data, we can identify China, India, and the United States as countries that require focused attention and control. Therefore, implementing corresponding plastic reduction measures for these three countries will have a positive impact on reducing the global consumption of PET plastics.

3.3. Variations in Metabolic Efficiency Indicators in Different Scenarios

Under a single scenario, the changes in metabolic indicators vary among different countries, as shown in Figure 6. From the perspective of individual scenarios, scenario of S1–S4 result in improvements across the *RR*, *CMUR*, and *CLCR* indicators, with S1 scenario showing the most notable increase. In the case of scenario S5, which prohibits the trade of waste plastics, there will be a decrease in circularity for Brazil, South Korea, South Africa, Thailand, and India. This is because these countries have lower domestic waste plastic processing capabilities. Brazil, South Africa, and India lack incineration facilities, with most waste being landfilled [72–74]. Moreover, India's plastic waste management is insufficient, with much of it not entering sanitary landfills but rather being openly burned [70,71]. Thailand has a high landfill rate of up to 85% [13,75,76]. Although South Korea has developed better resource utilization for plastics, its recycling efficiency is not high, at less than 70% [77,78]. And, since the volume of waste plastic trade is relatively small, the impact is not significant, generally below 10%.

Comparing scenarios S6 and S7, closed-loop recycling (S6) does not significantly improve *RR* and *CMUR*, but has a notable effect on *CLCR*. In scenario S7, *RR* and *CMUR* significantly decrease in Mexico, Europe, and Japan due to the saturation of the recycling market in these countries. This is also a benefit of closed-loop recycling, avoiding the waste that comes from flooding the market with low-cost materials. Looking at the combined scenarios S8–S11, there is a significant reduction in *RR*, *CMUR*, and *CLCR*, which is better than those of individual scenarios. However, S12 and S13 generally lead to a decrease in *CLCR*, especially in Mexico, Europe, and Japan. Even with the adoption of advanced waste treatment methods, without implementing closed-loop recycling, recycled materials are likely to reach saturation in these countries.

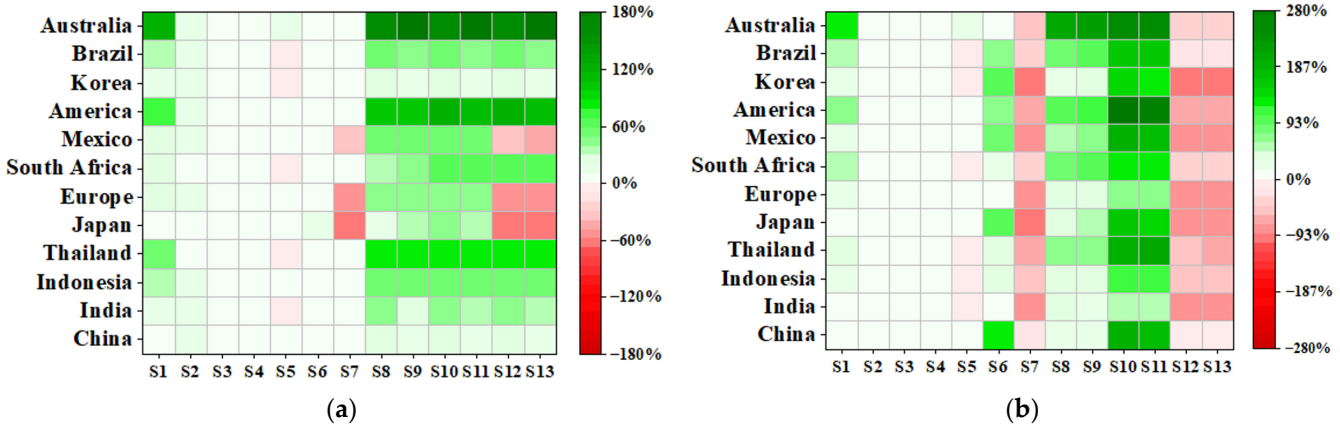


Figure 6. *Cont.*

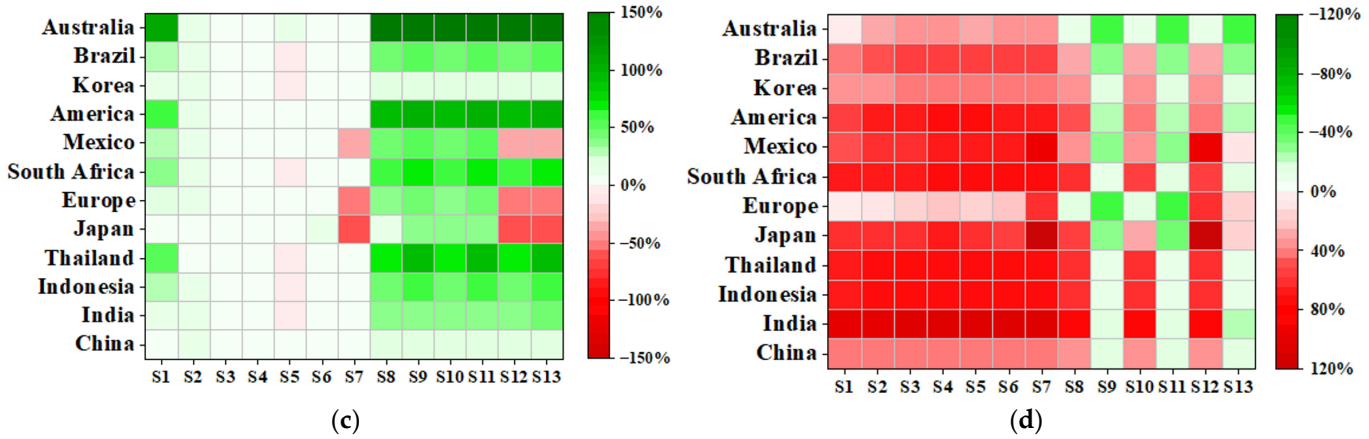


Figure 6. The percentage changes in indicators for each country under scenarios S1–S13 compared to the baseline scenario by 2030. (**a**) *RR*, (**b**) *CLCR*, (**c**) *CMUR*, (**d**) *VMC*. Green indicates an improvement in circularity indicators or a reduction in the use of virgin resin, while red indicates a decline in circularity indicators or an increase in the use of virgin resin.

However, for the circular economy, a very important goal is to reduce the use of virgin materials, achieving reduction at the source. *VMC* effectively addresses the shortcomings of the other three indicators. With demand increasing, regardless of the levels of *RR*, *CMUR*, and *CLCR*, *VMC* always increases (as shown in Figure 6). This finding suggests that focusing solely on *RR*, *CMUR*, and *CLCR* is insufficient to assess a country's transition towards a circular economy. In other words, even if *CMUR* is at 80%, the absolute quantity of *VMC* (representing the remaining 20%) would be much larger if the total demand for PET increases from 5 million tons to 30 million tons over 50 years. This emphasizes the importance of waste hierarchy's first step: prevention [46]. Therefore, if the aim of the circular economy is to minimize reliance on virgin materials to the greatest extent possible, then absolute indicators like *VMC* should complement relative indicators, and controlling demand is an essential strategy that cannot be overlooked.

3.4. GHG Emissions of PET Plastic Supply Chains in 2020

The following shows the greenhouse gas emissions of the PET supply chain in different countries in 2020, as illustrated in Figure 7. The total supply chain emissions of PET plastics amounted to 534.6 Mt of CO_2 equivalent, with the production of PET resin contributing the largest share, accounting for 46.1%. Similar to the online food delivery service industry, the production process of raw materials constitutes the largest share of packaging greenhouse gas emissions, making it the primary source of emissions [79].

Following the production phase, the PET manufacturing stage is the second largest contributor, accounting for 44.7% of emissions. Within the manufacturing stage, the manufacture of PET fibers stands out as the principal source, contributing 144.5 Mt of CO_2 equivalent, which represents 60.5% of total manufacturing emissions. The manufacture of PET bottles and films follows, with contributions of 34.8% and 3.5%, respectively. Emissions from other products account for a mere 1.2%. The production volumes of PET fibers and bottles are substantial. Current research indicates that the upstream chemicals used in PET fiber production and the energy consumed during PET bottle manufacturing can harm human health and exacerbate global warming [79]. Within the entire PET supply chain, the waste disposal phase emits the least greenhouse gases, accounting for only 9.2%. Incineration and sorting are the primary sources of greenhouse gas emissions during the PET waste disposal phase, contributing 40.5 Mt and 25.0 Mt of CO_2 equivalent, respectively. Although some electricity is recovered during the incineration process, the offset in CO_2 is far less than the amount emitted. In the recycling and remanufacturing process, the use of recycled materials reduces the production of virgin PET plastic, offsetting 16.3 Mt of CO_2 equivalent.

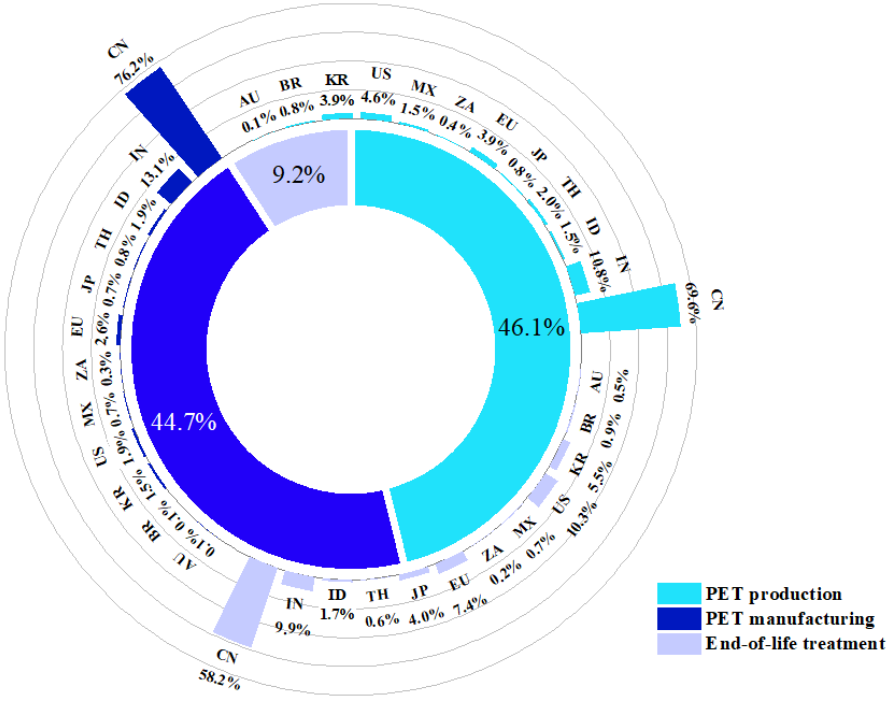


Figure 7. Greenhouse gas emissions by various countries in 2020. Countries or regions are abbreviated according to the ISO 3166-1 alpha-2 standard. CN: China, EU: Europe, KR: Korea, IN: India, US: America, ID: Indonesia, TH: Thailand, JP: Japan, MX: Mexico, BR: Brazil, AU: Australia, ZA: South Africa.

From the perspective of individual countries, the top six countries in terms of emissions during the production phase are China (69.6%), India (10.8%), the United States (4.6%), Europe (3.9%), and South Korea (3.9%), totaling an impressive 92.8% share. In the manufacturing phase, India and China are the major emitters, together accounting for 89.3%. Looking at the waste disposal phase, the primary emitting countries are China, the United States, India, Europe, South Korea, and Japan, with these countries' combined carbon emissions making up 95.3% of the total. Looking at the entire life cycle of PET, China and India are major emitters. Therefore, it is imperative to prioritize the development of low-carbon technologies in these two countries and implement effective measures to reduce their emissions. This may include initiatives such as improving production processes, promoting clean energy adoption, enhancing waste management, and increasing recycling rates [80]. By focusing on these countries, the carbon emissions of the global PET plastic supply chain can be more effectively controlled and reduced.

Although India and China are major emitters, some of the resin and products are not consumed domestically but are exported to other countries, causing greenhouse gas flows due to trade. As shown in Figure 8, China, India, South Korea, Indonesia, and Thailand are net carbon exporters, with China being the largest, exporting up to 23.8 Mt. The exports from the other countries are 7.4 Mt, 3.8 Mt, 3.3 Mt, and 1.8 Mt, respectively. Europe, the United States, and Japan are major carbon importers, with import volumes of 0.8 Mt, 0.7 Mt, and 0.69 Mt, respectively. However, it is important to note that the carbon emission transfer caused by the PET plastic trade accounts for less than 5% of the total carbon emissions, compared to other industries such as the steel industry [81]. Therefore, the carbon emission transfer resulting from the PET industry trade has a relatively minor impact on overall emissions compared to other sectors.

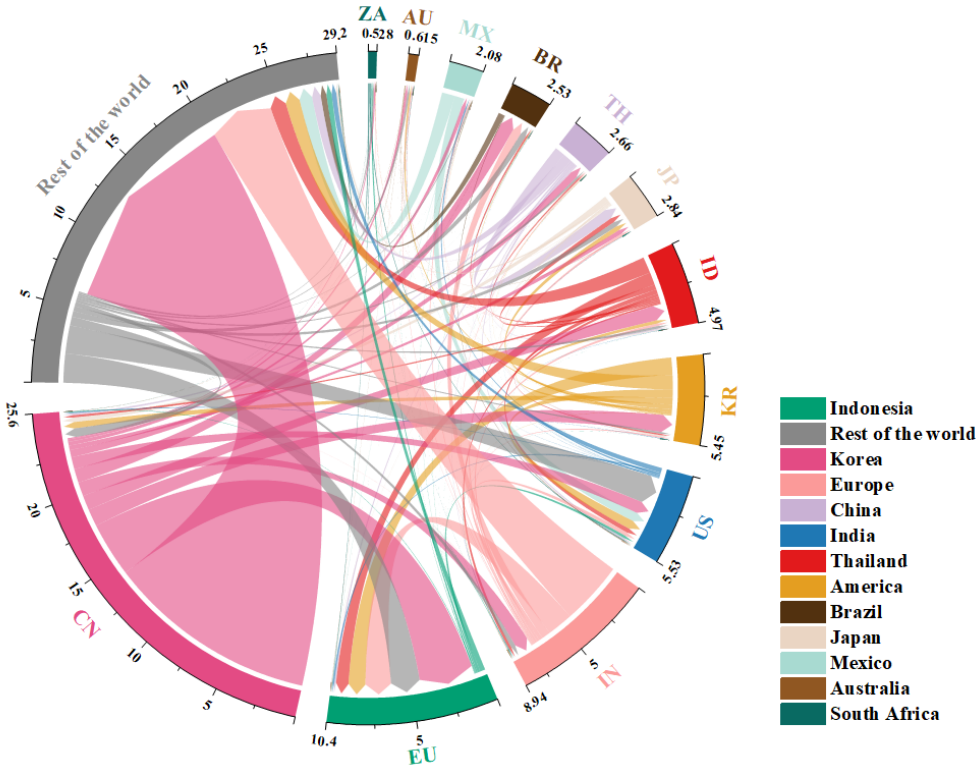


Figure 8. The greenhouse gas transfers caused by trade in various countries in 2020, in units of Mt (million metric tons). Countries or regions are abbreviated according to the ISO 3166-1 alpha-2 standard. CN: China, EU: Europe, KR: Korea, IN: India, US: America, ID: Indonesia, TH: Thailand, JP: Japan, MX: Mexico, BR: Brazil, AU: Australia, ZA: South Africa.

3.5. Variations in Greenhouse Gas Emissions in Different Scenarios

The changes in carbon emissions varies by country under different scenarios, as shown in Figure 9. In scenarios S1–S3, carbon emissions are reduced, with the enhancement of waste collection showing the best results. For scenario S4, which involves increasing waste incineration and reducing landfill, all countries except India and Indonesia show a clear increase in carbon emissions. Although some studies suggest that landfilling might generate more greenhouse gas emissions than incineration [82], the fact remains that plastics can remain un-decomposed in landfills for hundreds to thousands of years, whereas incinerating plastics produces a significant amount of greenhouse gas emissions. Moreover, the electricity recovered from incineration is far from sufficient to offset burning emissions. The decrease in emissions for India and Indonesia is due to the lack of waste management infrastructure in these countries [70], where a large amount of plastic waste is directly burned without energy recovery [71]. The consideration of energy recovery in scenario S4 would lead the two countries to experience improvements.

In the scenario S5, which involves banning the trade of plastic waste, countries like Brazil, South Africa, Thailand, and India experience an increase in greenhouse gas emissions due to their inadequate waste infrastructure. South Korea, due to its incineration rate being higher than other countries, experiences increased emissions when waste plastics are not exported but processed domestically [78,83].

Regarding S6 and S7 scenarios, apart from Europe, Japan, and Mexico, the overall impact on emissions variation is not significant, with the highest impact being only 2.5%. The variation is due to the different manufacturing loss rates for producing various plastic products, which leads to an increase or decrease in the demand for virgin plastics. However, since the manufacturing loss rates are quite low, the impact is minimal. Nonetheless, in the S7 scenario, greenhouse gas emissions significantly increase in Europe, Japan, and Mexico due to the saturated recycled PET market, which leads to increased demand for

virgin plastic products. When the recycling market is saturated, developing a closed-loop economy can, to some extent, mitigate greenhouse gas emissions.

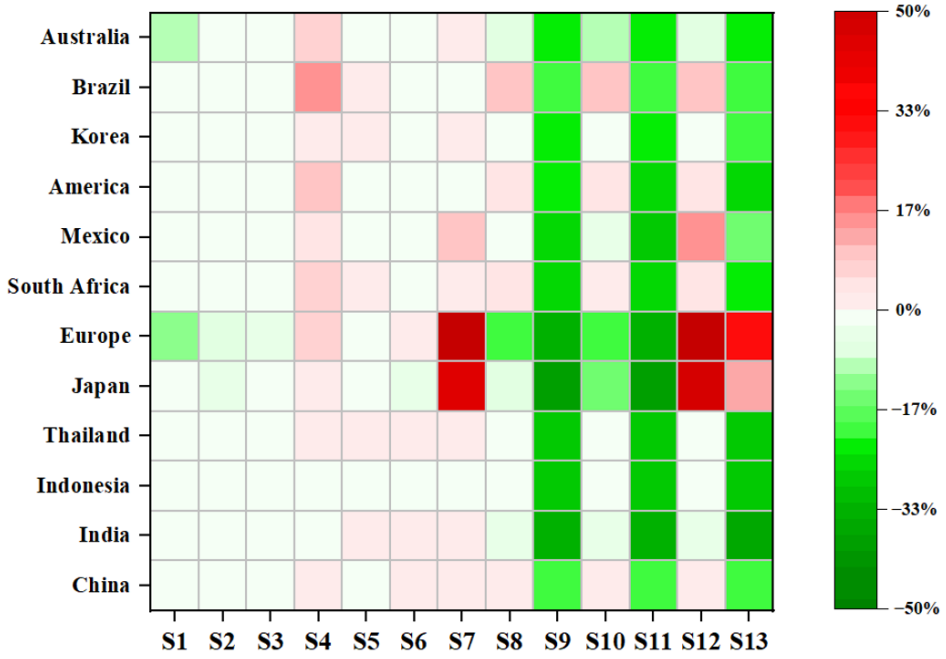


Figure 9. The cumulative change in greenhouse gas emissions from 2020 to 2030 under scenarios S1–S13 compared to the baseline scenario.

In the comprehensive scenarios S8–S13, scenarios that control demand, such as S9, S11, and S13, are significantly better than those without demand control, such as S8, S10, and S12. Even with the implementation of advanced end-of-life treatment technologies like those in S8 and S10, some countries may still see an increase in greenhouse gas emissions, and countries that do manage to reduce emissions can only achieve a maximum reduction of 20%. This is primarily due to emissions from plastic incineration; although incineration can reduce the volume of plastic waste, it increases carbon emissions. Under demand control scenarios, S9, S11, and S13, all countries except for Europe and Japan in scenario S13 see a significant decrease in greenhouse gas emissions, with a general reduction of more than 20% and Europe achieving reductions of up to 40%. In scenario S13, Europe and Japan experience an increase in greenhouse gas emissions due to the saturation of recycled materials. Overall, waste incineration is not the best treatment method for plastics waste as it leads to substantial greenhouse gas emissions. Furthermore, research has found that controlling demand and managing the saturation of the recycled materials market are important emission reduction measures. Section S6.2 displays the variation in sources of greenhouse gas in different scenarios by country.

4. Discussion

Through an in-depth analysis of the global material flow characteristics of PET plastics, this study found that as of 2020, the global production of virgin PET resin reached 72,977 kt. In terms of consumption, PET fiber accounted for the largest share at 61%, followed by PET bottles (25.5%), PET film (11.5%), and other PET products (2%). The high consumption of fiber coupled with low recycling rates underscores the importance of developing fiber recycling technologies to improve PET industry recycling rates [84]. From a holistic supply chain perspective, the production, manufacturing, consumption, and disposal of global PET plastics are primarily concentrated in four countries: China, India, the United States, and Europe. Other studies have also confirmed this conclusion. China, as the largest producer of plastics, has seen a rapid increase in the production of primary plastics over the past 20 years [85]. India, the United States, and Europe are also major consumers of PET

products [86]. This research finding provides important data support for the development and management of the global PET plastic industry, assisting countries in formulating more precise policies and measures to promote the industry's transition towards a more sustainable direction.

From the perspective of resource efficiency indicators such as *RR*, *CMUR*, and *CLCR*, Japan, Europe, and Mexico rank in the top three, demonstrating their superiority in the utilization and circularity of waste PET plastics [87–89]. The high recycling rates in these countries indicate significant achievements in PET plastic recycling. Conversely, countries like Thailand, South Africa, Australia, and the United States have lower recycling rates, suggesting challenges in PET plastic recycling that require increased policy support and investment to enhance circularity levels [60,75,90,91].

In the analysis of resource metabolism indicators under 13 circular economy scenarios, it was found that as long as demand continues to grow—regardless of the levels of *RR*, *CMUR*, and *CLCR*—the *VMC* indicator shows an upward trend, sharply increasing with demand. Some studies have also found that reducing production and consumption is a prerequisite for achieving a truly circular plastic economy [92]. This finding emphasizes the importance of demand control; besides measures such as increasing recycling, reducing waste at the source is also crucial [93]. Therefore, when formulating circular economy policies, countries should take this into account and implement corresponding measures to control and manage demand, thereby achieving sustainable resource utilization and the development goals of the circular economy.

From the perspective of greenhouse gas emission reduction, comprehensive analysis indicates that the global PET plastic supply chain emitted a total of 53,461.4 million metric tons of carbon dioxide equivalent in the given year. Specifically, production emissions of PET resin account for a significant portion, consistent with much of the existing research, which identifies resin production stages as the most carbon-intensive [79]. Attention needs to be directed towards emissions control in the upstream of the PET supply chain, particularly in the production of raw materials. However, it is important to note that the carbon emissions resulting from the PET plastic trade account for less than 5% of the overall total emissions, indicating a relatively minor impact compared to other industries such as the steel sector [81]. This conclusion provides important insights for future emission reduction policy formulation. From the perspective of individual countries, China and India rank among the top three in emissions across production, manufacturing, and disposal stages. These two countries together account for over 80% of the total emissions, consistent with numerous studies identifying China and India as major carbon emitters [10,94]. Therefore, focusing on these countries and prioritizing their management and emission reduction measures will have a more effective impact on controlling and reducing carbon emissions in the global PET plastic supply chain. This conclusion underscores the importance of coordinated cooperation on a global scale to address the environmental challenges posed by the PET plastic industry and to advance towards more sustainable development goals [95].

Through comprehensive comparative analysis of greenhouse gas changes in various countries under 13 circular economy scenarios, we have drawn some important conclusions. Even with the adoption of advanced end-of-life treatment technologies, under high circularity scenarios, greenhouse gas emissions in various countries may increase if demand is not restricted [28]. However, under scenarios where demand is restricted, most countries have achieved significant emission reductions. The emission reduction effects in various countries generally exceed 20%, with Europe even achieving a reduction of up to 40%. These findings emphasize the importance of limiting consumer demand and the necessity of implementing appropriate policies to promote the circular economy [92]. Therefore, future policymakers and stakeholders should prioritize the importance of limiting consumer demand and actively take measures to achieve significant reductions in global greenhouse gas emissions, promoting global progress towards a more sustainable development direction.

In summary, while the development of advanced waste treatment technologies can effectively reduce the quantity of waste, their effectiveness in reducing greenhouse gas emissions is limited when demand continues to grow. Therefore, we need to start from consumer demand and consider how to guide consumers to reduce their demand for PET products. One feasible approach is to increase consumer awareness of the environmental impact of products by implementing measures such as eco-labels and carbon labels [96–98], thereby guiding consumers to prefer more environmentally friendly products. Additionally, encouraging consumers to adopt practices such as reusing plastic bottles and other reusable products can reduce the quantity of single-use plastic products [99]. These actions may have a positive impact on reducing greenhouse gas emissions, so one future research direction is to quantify the emission reduction effects of these measures. By thoroughly researching and accurately measuring the impact of these actions on greenhouse gas emissions, we can better guide policy formulation and implementation, promoting the process of sustainable development. Therefore, future research should focus on quantifying the emission reduction potential of these consumer guidance measures and exploring how to incorporate them into the management and governance of the global PET plastic supply chain.

Equally important is the strengthening of the development of localized life cycle databases. Particularly in some countries, especially developing ones, where there is a lack of relevant life cycle data [28], we have to rely on data from other countries or use globally coordinated electricity and heat factors [100]. However, greenhouse gas emissions reduction is a global challenge, and to more accurately guide emission reduction actions, reliance on local data from each country is necessary [101,102]. Therefore, countries should strengthen the construction of localized life cycle databases. This includes collecting and organizing data on domestic production, consumption, and waste disposal stages, and establishing country-specific emission factor data. Through localized data, we can more accurately assess and quantify the environmental impacts of different industries and activities, providing the scientific basis for the formulation of targeted emission reduction policies and measures.

5. Conclusions

The focus of this study is to establish the flow of PET plastic throughout the supply chains of various countries using material flow methods and to calculate emissions at various stages of the life cycle using Life Cycle Assessment methods. This aims to provide scientific evidence for improving PET resource utilization efficiency, reducing plastic waste, and mitigating greenhouse gas emissions. This study found that as of 2020, global production of primary PET resin reached 7297.7 kt, with only 23% recycled into recycled materials, 35% incinerated, and the remaining 44% landfilled or lost to the environment. From a national perspective, the production, manufacturing, consumption, and disposal of global PET plastic are mainly concentrated in China, India, the United States, and Europe. These findings provide important data support for the development and management of the global PET plastic industry, assisting countries in formulating more precise policies and measures to promote the industry towards a more sustainable direction. Despite improvements in resource efficiency in various circular economy scenarios, the *VMC* indicator shows an upward trend as long as demand continues to grow, regardless of the level of circularity in each country. This underscores the importance of controlling demand. In addition to implementing measures such as increasing recycling, reducing the volume of plastic at the source is also crucial. Therefore, when formulating circular economy policies, countries should consider this comprehensively and take corresponding measures to control and manage demand, in order to achieve sustainable resource utilization and circular economy development goals.

The total life cycle emissions of global PET plastics amount to 534.6 Mt of CO_2 equivalent, with PET resin production accounting for 46.1% of that amount, product manufacturing for 44.7%, and disposal phase for 9.2%. It is clear that the focus of emission control

should be concentrated on PET resin production. From the perspective of individual countries, China and India rank among the top three in production, manufacturing, and disposal phases, collectively contributing to over 80% of the overall emissions. Therefore, prioritizing management and emission reduction measures in these countries will effectively control and reduce carbon emissions in the global PET plastic supply chain. However, analysis of carbon emission transfers resulting from the PET plastic trade indicates that the carbon emissions generated by the PET industry trade account for less than 5% of the total carbon emissions, indicating a relatively minor impact on overall emissions. This conclusion suggests that the influence of the global PET plastic trade on carbon emissions is relatively limited, providing important insights for future emission reduction policy formulation. Through comprehensive comparative analysis of greenhouse gas changes in various countries under 13 circular economy scenarios, several important conclusions have been drawn. Even with advanced end-of-life treatment technologies, in high circularity scenarios, emissions of greenhouse gases in each country may increase if demand is not restricted. However, under restricted demand conditions, most countries have achieved significant emission reductions. The emission reduction effects of most countries exceed 20%, with Europe even achieving up to a 40% reduction in emissions. Therefore, policymakers and stakeholders in the future should emphasize the importance of restricting consumer demand and actively take measures to achieve significant reductions in global greenhouse gas emissions, promoting the world towards a more sustainable development direction.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su16103926/s1, Table S1: The ISO country ID and abbreviation of country names; Table S2.1: PET resin production by country; Table S2.2: Manufacturing proportion of PET products by country; Table S2.3: Growth rate of PET product demand by country; Table S2.4: Collection rates of PET products by country; Table S2.5: Recycling efficiency by country; Table S2.6: Incineration and landfill rates; Table S2.7: Incineration efficiency; Table S2.8: PET commodity codes and contents; Table S2.9: Plastic waste content; Table S3.1: Change of collection rate in 2020–2030; Table S3.2: Change of sorting rate in 2020–2030; Table S3.3: Change of recycling efficiency in 2020–2030; Table S3.4: Change of incineration and landfalling rate in 2020–2030; Table S4: Sources of lifecycle data; Table S5: Sensitivity and uncertainty analysis; Section S6: Results by country; Section S6.1 Results for MFA; Section S6.2 Results for LCA. References. [11,19,21,30,43,45,70,72,73,75,103–171] are cited in Supplementary Materials.

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