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China's Import of Waste PET Bottles Benefited Global Plastic Circularity and Environmental Performance

Zijie Ma^{a, b, c}, Morten W. Ryberg^d, Peng Wang^{a, c}, Linbin Tang^{a, b, c},

and Wei-Qiang Chen^{a, b, c}*

^a Key Lab of Urban Environment and Health, Institute of Urban Environment, Chinese Academy of Sciences, Xiamen 361021, PR China

^b University of Chinese Academy of Sciences, Beijing 100049, PR China

^c Fujian Institute of Innovation, Chinese Academy of Sciences, 1799 Jimei Road, Xiamen, Fujian 361021, PR China

^d Quantitative Sustainability Assessment Group, Sustainability Division, DTU Management, Technical University of Denmark (DTU), Produktionstorvet, Building 424, 2800 Kgs. Lyngby, Denmark

E-mail: zjma@iue.ac.cn, moryb@dtu.dk, pwang@iue.ac.cn, linbintang@iue.ac.cn, wqchen@iue.ac.cn

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ABSTRACT

Polyethylene terephthalate (PET) used to account for $\approx 50\%$ of China's waste plastics import. In 2018, the Chinese government banned the import of waste plastics due to the environmental and health burdens caused by the waste treatment processes. However, the recycling of waste PET also helps avoid the production of virgin PET and several corresponding environmental impacts such as fossil resources use and carbon emission, which remain unquantified. We combine material flow analysis and life cycle assessment to map the PET bottle cycles and evaluate the relevant environmental performances during 2000-2018 in China. The cumulative recycling of PET bottles amounted to 78 million tons (Mt) in China during the studied period. Among them, 29 Mt waste PET bottles (37% of total recycling) were imported from abroad and accounted for 40% of the world's total export. Most waste PET bottles in China was recycled to produce PET fibers, which significantly improved global PET circularity, reduced the use of virgin PET material, and saved about 109 Mt oil-eq of fossil resources (e.g. coal and oil) use and avoided 233 Mt CO₂-eq emissions. Despite these benefits, the environmental burdens with regional impacts during waste plastics treatment should be significantly reduced, and technologies for close-loop, namely bottle-to-bottle, recycling of PET should be further developed and widely applied.

INTRODUCTION

China has been the world's largest post-consumer plastics importer since 21st century. The import ban on all kinds of post-consumer plastics from 2018 issued by Chinese government significantly reshape the global structure of post-consumer plastics flows.¹ The original intention of the waste ban is to protect China's environment and human health,² but from the perspective of whole life cycle, the imported waste plastics has environmental benefits (especially in terms of resource saving and carbon emission reduction). Currently, the concrete environmental benefits of imported waste plastics have not been explored yet. Polyethylene terephthalate (PET), as one of the most widely used plastic materials (i.e. 18.8 Mt produced in 2015, about 5% of total plastics production³), has become the most favorable packaging material world-wide for water and soft drinks. China has become the largest PET bottle consumer in the world since 2010,⁴ and the largest share of post-consumer plastics imported by China before 2018 is PET bottle.⁵ The imported waste PET bottles are used to produce regenerated fibers in China, while the amount of them plummeted due to the waste plastics import ban. Considering the resources attributes of imported waste plastics, the potential benefits of waste PET bottles should be carefully measured.

The rapid increase in PET bottle consumption is accompanied by the booming of PET production, which causes the various environmental impacts.^{6,7} Most of the studies on the environmental impact of PET bottles either focused on measuring the

environmental impacts caused by the different waste management scenarios (such as incineration, landfill or recycling)^{8–12} or evaluated the different methods of reprocessing reclaimed PET resins using life cycle assessment (LCA).^{13–15} However, on the national level, the contributions of waste PET bottles trade on China's domestic PET bottles cycle and its corresponding environmental performance has not been studied yet, which hinders the comprehensive analysis of solid waste trade policies.

Material flow analysis (MFA) is a widely used approach to trace the source, path, intermediate process and final destination of the materials along their life cycle within a specific geographical area,¹⁶ and were used for metals,^{17–21} waste paper,²² and plastics,^{23–26} while there is no specific research about China's PET bottles. The MFA of PET bottles, combined with LCA, can provide a basis for further study of the environmental impact of the whole life cycle of PET bottles.

Given that the global waste flows are frequently interrupted by trade bans, the comprehensive study of the impact of imported waste PET bottles in China can bring policy insights for Southeast Asia and other countries. Thus, we first conduct a retrospective analysis of all PET bottles produced, consumed, imported, and recycled within China annually from 2000 to 2018. Then, we provide an estimate of the environmental impacts expressed as impacts on human health, ecosystem quality, resources, and global warming associated with the handling and management of the PET material flows in China. The rest of this paper is organized as follows: Section 2

explains the detailed methods and data. Section 3 reveals the contributions of waste PET bottles trade on global plastic circularity and its corresponding environmental performance. The uncovered environmental damages caused by imported PET bottles and the corresponding suggestions for plastic waste treatment in China after the trade ban are further discussed in Section 4. The final section summarizes the contributions and provides policy suggestions.

MATERIAL AND METHODS

Framework

The framework of our study is presented in **Figure 1**. The spatial boundary is mainland China, and the temporal boundary is annually from 2000 to 2018. One part of this study uses the MFA method to describe the flows from the production to the waste management (**Figure S2**), including domestic flow, waste flow, and trade flow. This part quantifies the material cycle of China's PET bottle and provides necessary data to calculate the results of the environmental impact. Another part uses the LCA method to calculate the environmental benefits and impacts by multiplying the different flows with PET process impact intensities (impacts per kilogram managed). By integrating the MFA with LCA, the comprehensive analysis of resources and environmental effects of dynamics material flows can be assessed.

Figure 1. The research framework of material flow analysis (MFA) and life cycle assessment (LCA) of PET bottles.

Mapping China's PET bottles flow along its life cycle

The historic material stocks and flows along China PET bottle cycles are traced using a framework described in **Figure S2**. Five processes (production, fabrication, manufacturing, in-use, and waste management) along the PET bottle life cycle (see SI 1 Section S1.2 for details) are investigated by defining five variables: input, import, export, output, and loss. The relationship among these five variables follows the law of conservation of mass, as Eq. (1) shows:

$$F_{PET,i,j}^{input} + F_{PET,i,j}^{import} = F_{PET,i,j}^{output} + F_{PET,i,j}^{export} + F_{PET,i,j}^{loss} \quad (1)$$

where i is the index for each life stage, j is the index for each year from 2000 to 2018. $F_{PET,i,j}^{input}$ is the different forms of PET in material flows demanded by life stage i in year j ; $F_{PET,i,j}^{import}$ is the import of different forms of PET commodities in stage i

in year j ; $F_{PET,i,j}^{export}$ is the export of different forms of PET commodities in stage i in year j ; $F_{PET,i,j}^{loss}$ is the quantity losses of PET in life stage i in year j ; $F_{PET,i,j}^{output}$ is the different forms of PET in final products generated from stage i in year j .

All flows and stocks are calculated using a dynamic MFA model. Three approaches are used to calculate the flows: use of data from industrial statistics yearbook, calculation by transfer coefficients estimated from reports, and derivation by the mass balance principle.²⁷ We assume that all the consumed PET bottles are directly scrapped in the same year without the in-use stock remains in the society. Notably, the loss during the whole life cycle of PET bottles can be divided into two parts: one part is caused by processing and production which will ends up into the environment; the other part is caused by waste PET bottles that are not recycled due to quality reasons. These waste PET bottles will be mixed with domestic waste and then be landfilled or incinerated.¹² The detailed data source of each flow is provided in SI 1 Section S1.3.

Environmental impacts quantification

The corresponding impacts associated with PET bottle cycle in China are characterized in terms of impact to human health, ecosystem quality, resources, and climate change, assessed by coupling the material flows for the processes covered in the MFA with a life-cycle inventory over resource uses and environmental emissions (collectively termed “elementary flows”) from each process. The elementary flows where hereafter multiplied with characterization factors from the ReCiPe 2016 life-

cycle impact assessment (LCIA) methodology²⁸ as implemented in OpenLCA v.1.10. This allows for translating the elementary flows into potential impacts on humans and the environment. The functional unit for the environmental LCA in this study is “production and waste management of PET bottles in China in the period 2000 to 2018”. Following,²⁹ the environmental impacts are expressed concerning the three areas of protection, i.e. human health [expressed as disability-adjusted life-years; DALY], ecosystem quality [expressed as species lost integrated over time; species·year], resources [expressed as the extra costs involved in future mineral and fossil resource extraction; US\$ using 2013 as reference year]. Moreover, impact specifically for climate change [expressed as kg CO₂-eq] is also indicated because of the particular importance of this impact category.³⁰ This allows for quantifying the total impacts of PET bottle production and handling in China as well as the impacts associated with the different processes that are part of China's PET bottle cycle.

Meanwhile, we reveal environmental benefits contributed by the recycling of PET bottles from the perspective of reducing resource input. The recycling of PET bottle is modelled as an alternative to virgin PET production to achieve resources benefits. Hereafter, the recycled PET production is used as input for subsequent production of PET fibers. The subsequent fiber production is not considered part of the recycling process. We model environmental benefits of recycling based on the Product Environmental Footprint methodology recommended by the European Commission.³¹

Here, we apply the Circular Footprint Formula (CFF) with a recycling quality ratio of 0.9 for packaging PET.³¹ Incineration of PET bottles with energy recovery is modelled to substitute conventional generation of electricity and heat in China (see SI 2). The generation of the electricity that is used in the different life-cycle processes is modelled as being temporally dynamic from 2000 to 2018. The relative share of different energy generation sources and their temporal development in China is retrieved from the International Energy Agency.³² The original data is extracted for the years 2000, 2005, 2010, 2015, and 2017. Linear interpolation is used to estimate the electricity grid mix in between years while 2018 was assumed to be equal to 2017. Technologies that matched the electricity generation sources are selected based on available processes in ecoinvent 3.4 (see SI 2 for an overview of used LCI processes). Differentiation between the different sources of electricity (see SI 2 for overview of electricity sources) was based on the default technology share used by the “State Grid Corporation of China” in the process “market for electricity, high voltage, cut-off” in ecoinvent 3.4. The mix of sources for heat generation in China is modelled based on International Energy Agency³² and is used as heat input for heat consuming processes (see SI 2).

RESULTS

Mapping the flows of waste PET bottles

Between 2000 and 2018, the cumulative amount of waste PET bottles was ~78 million tons (Mt) in China (**Figure 2(a)**), equivalent to ~7 tons waste PET bottles generated every minute. Approximately 49 Mt (63%) of these waste PET bottles were generated domestically and 29 Mt (37%) were imported from other countries. Notably, China is a net importer of waste PET bottles, and the amount of imported waste PET bottles is 290 times of that of the exported ones. The recycling capacity of waste PET bottles in China is 1.5 times that of domestic generation, indicating that the surplus recycling capacity far exceeds the domestic generated amount. Of 78 Mt total scrapped PET bottles, ~90% were recycled in China. The recycling of China's waste PET bottles is mainly open-loop recycling, and waste PET bottles are mainly used to manufacture recycled fiber products and then processed into clothes. However, according to China National Resources Recycling Association (CRRA) report,³³ only 5% China's recycling technology applies the world's advanced recycling technology bottle-to-bottle (BTB) recycling. These BTB recycling bottles are used to produce "non-food contact grade" PET bottles (such as pesticide bottle), because the current BTB recycling technology in China is still relatively backward, and the safety of recycled products cannot be guaranteed, which may result in harm to the health of consumers.³⁴ Therefore,

China's current policy does not allow the use of recycled plastics in “food contact” packaging,³⁵ unlike other nations.

The amount of domestically generated waste PET bottles has increased 4.6 times from 2000 (0.9 Mt) to 2018 (4.4 Mt) and has exceeded the amount of imported waste PET bottles since 2003 (**Figure 2(b)**). After the implementation of China's ban on the imports of all kinds of waste plastic products, the amount of net import recycling plunged in 2018 (**Figure 2(c)**). The impact of the import ban on global waste plastics trade caused a huge shortage in China's recycled fiber raw material.

Figure 2. The flow of waste PET bottles in China. (2000 to 2018; Unit: Million ton. (a) Overview, (b) generation and (c) recycling. Note that domestic recycling and net import recycling refer to the sources of recycling PET bottles are domestically scrapped, and net imported respectively.)

Contribution of waste PET trade for global and China's PET circularity

Polyester is the raw material of PET bottle production and China is the world's largest polyester producer. China's polyester production capacity accounts for over 55% in the world,³⁶ and the polyester self-sufficiency rate exceeded 100% from 2012 to 2015.³⁷ Therefore, the total production of China's PET bottles accumulated to 52 Mt during the 19 years (**Figure 3(a)**). All these PET bottles are assumed to be scrapped immediately after use, and thus the amount of domestic scrapped completely comes from domestic consumption. Although the increasingly reliant on coal for polyester production in China can save petroleum consumption, which also comes with its environmental costs.³⁸ Fortunately, the excellent performance of PET bottle recycling in China can help to reduce some resources input. We find 90% of the waste PET bottles in China are used to make recycled PET fibers, which can be further processed into textiles. Besides the domestic generated PET bottles, China also imports many waste PET bottles to meet domestic demand for recycled PET fibers (**Figure 3(b)**). Thus, the huge PET bottles recycling capacity in China saved the use of virgin PET fiber and polyester, and further saved the use of two nonrenewable resources (oil and coal).

Notably, there is a severe overcapacity issue in China's polyester production,³⁷ which drives China to become a major exporter of upstream products (bottle grade PET chip and PET bottle embryo). The export amount of them is rising with an annual rate of 45% and 21% during the 2000 to 2018 respectively. With the increase of PET bottle

consumption and the implementation of China's waste plastic import ban since 2018, China can meet domestic PET bottle production and domestic recycled PET fiber market demand by improving resource utilization and recycling rate.

Figure 3. Material flow analysis of PET bottles in China. ((a) Total amount from 2000 to 2018. All flows are accumulated to present the overall PET bottle related products use in China during the past nineteen years; the width of the edge represents the weight of each material flow in the specific temporal boundary; the color of flows differentiates the different stages in PET bottle's life cycle. (b) Flow of each kind of PET bottle related products.)

Sourcing waste PET bottles imports

We map the importers of China's waste PET import in **Figure 4**. The total amount of waste PET bottles imported by China reaches 29.1 Mt for 19 years, the weight of which is equivalent to four thousand Eiffel Towers. The trade partners of China's waste PET bottle are all over the world, and Asia is the largest region of China's import of waste PET bottles with a total of 17.1 Mt for 19 years followed by the Americas (5.9 Mt). Notably, Europe exports only 3.4 Mt of waste PET bottles in these years because of its well-developed recycling system.³⁹ The top three exporters are Japan (4.2 Mt), the United States (3.4 Mt), and Thailand (1.6 Mt, because of entrepot trade). The amount of waste PET bottles exported from these countries plunged after the implementation of China's waste plastics import ban in 2018 when China's total amount of waste plastics import was only 13 kiloton (kt) (**Figure S4**). In the period concerned, the United States and Japan were net exporters of waste PET bottles, while Thailand and Indonesia were net exporters before 2017 and transform to net importers in 2018 (**Figure S5**). This may be related to the plastic waste trade flows largely redirected to Southeast Asian countries after China's import ban.⁴⁰

Figure 4. The direct sources of waste PET bottles imports in China from 2000 to 2018. (*Total amount of 2000 to 2018; Unit: Million ton. Arrows in each panel show the main flows of China's imports of waste PET bottles.*)

Environmental performance from PET material cycle in China

The results of the environmental performance of PET bottles management in China from 2000 to 2018 cover the processes and activities related to the production of new PET bottles and the management of waste PET bottles (incl. imported bottles). **Figure 5** shows the development in impacts on human health [DALY], ecosystem quality [species·yr], resources [US\$2013], and global warming [CO₂-eq], which altogether indicate the impacts on the three areas of protection as well as global warming. Results for other impact categories are part of ReCiPe 2016 and all feed into one of the three areas of protection (i.e. Human health, Ecosystem quality, and Resources can be found

in SI 2. About 174 Mt CO₂-eq were emitted from the PET bottles treatment (including recycling and waste disposal) in China during this period. In total, this also potentially led to 0.37 million DALY, 850 species yr, and a loss of about 0.9 billion US\$. The main contributor to impacts on human health and the environment is the production of PET and PET bottles. For instance, for global warming, the production corresponded to about 0.4 Gt CO₂-eq between 2000 and 2018, and annual emissions of CO₂-eqs increased by a factor 4.4 between 2000 and 2018. The impacts are due to the upstream production of the chemicals used for PET production and from electricity use during the manufacturing of PET bottles.

The high recycling rate of domestic and imported waste PET bottles substantially reduces overall costs from resource extraction. In fact, recycling 1 kg PET can save about 1.5 kg of fossil resources and avoid 3.2 kg of CO₂-eq emissions. During the 19 years, about 109 Mt oil-eq and 233 Mt CO₂-eq were saved due to the avoidance of virgin PET production in China, and around 37% of recycled PET bottles were imported from abroad which led that 40 Mt oil-eq of fossil resources saved and 85 Mt CO₂-eq emissions reduced from recycling of the imported PET bottles. Moreover, recycling also avoids the need for additional fossil resources for virgin PET production where we observe that resource savings from recycling from 2000 to 2018 reduce the increased costs from production by 98%. However, the import ban on PET bottles has a substantial effect on the net-impact as the impact from resource use increase by a

factor 7 from 2017 to 2018. Similar results are observed for impacts on human health and ecosystem quality. The average net-impact for human health and ecosystem quality between 2000 and 2017 was 0.02 DALY and 42 species·yr, respectively. In 2018, the impacts increased to 0.045 DALY and 101 species·yr for human health and ecosystem quality, respectively. Thus, an increase of about a factor 2.5 in 2018 compared to previous years. This means that the crediting of potential benefits to the environment and human health from the waste management and recycling of the imported PET bottles shift from China to other importing countries such as India.⁴¹

Figure 5. Temporal development in impacts on environmental impacts from production and waste management of PET bottles in China. (Between 2000 and 2018; Environmental impacts including human

health, ecosystem quality, resource costs, and global warming; Note that the waste PET bottles were used to produce PET fibers that can also be produced by virgin PET. Thus, the waste PET bottles recycling can reduce the virgin PET production that use to produce PET fibers.)

DISCUSSION

China's PET cycle after the waste trade ban. China, as a growing PET plastic consumer, increased its PET waste generation at an average annual rate of 10% from 2000 to 2018. The imported PET bottle waste accounted for 37% of total waste treated in China during the past 19 years. If the historical trend continues (see SI 1 Section 2.3 for details), the total domestic PET waste bottles are expected to reach ~11 Mt in 2030 (**Figure S6**), and it will take ~6 years for the domestically generated waste to reach the present total waste treatment capacity level in China. During this period, China will face a severe shortage of PET which was originally sourced from recycled PET bottles because of the waste import ban. Consequently, there will be more PET produced from the oil sector, generating higher CO₂ emission that contributes to global climate change. From the domestic perspective, the present PET bottle recycling rate in China is at a high level with an average rate of 88% and reached a peak in 2015 at 99%, which is relatively higher than that in Japan, Germany, and the United States (**Figure S7**). Nevertheless, such a high recycling rate of PET bottles is mainly driven by various waste pickers and informal small-scale recycling stations³³ rather than the formal

recycling chain as in the developed countries.⁴² After the trade ban, the present informal PET recycling chain in China cannot sustain with the demographic transition of the cheap labor force. Besides, compared to the imported plastic waste collected for treatment in waste centers, tremendous efforts are needed in the collection phase for those plastic waste from domestic sources, and the lack of corresponding incentives and sanctions lead to the low participation rate of residents in PET bottle recycling.⁴ Therefore, there is an urgent need to establish a formal system to enhance China's PET bottle recycling to fill the raw material gap caused by waste trade ban as required by the Ministry of Ecology and Environment of China.^{43–45}

The need for bottle-to-bottle recycling chain in China. The most preferred and advanced PET bottle recycling technology in the world is bottle-to-bottle (BTB) recycling, while waste PET bottles in China are widely used to produce synthetic textiles.³³ BTB recycling is called closed-loop recycling, while bottle to fiber or other products recycling is called open-loop recycling. The open-loop recycling is considered as downcycling because the value and quality of the PET is reduced.⁴⁶ The performance of closed-loop recycling is better than that of open-loop recycling in terms of energy consumption, greenhouse gas emissions and resource utilization rate.^{10–12} The recycling technology commonly used in developed countries is mechanical recycling (e.g. BTB) or chemical recycling,⁴⁷ but physical recycling is a widely used recycling technology in China.⁴⁸ In the process of physical recycling, waste PET bottles are separated,

crushed, washed, dried and granulated to produce recycled PET granules, and then the recycled PET granules are further processed into fiber grade PET chips that are finally used to produce recycled synthetic textiles products.⁴⁹ Indeed, mechanical recycling appears favorable as the environmental impact of it is found to be lower than chemical recycling¹² and physical recycling.¹¹ In fact, PET can be recycled four times before disposal in the landfill with bottle-to-bottle recycling but only once with physical recycling,¹¹ thus the life-time of the PET material is greatly expanded with mechanical recycling. Fortunately, China planned to implement a deposit system for beverage bottles in Hainan Province (as the first demonstration pilot). This is expected to greatly promote the BTB recycling of PET bottles in China.⁴²

Towards a balanced view of solid waste trade. Solid waste has dual attributes of resources and hazards, and the formulation of solid waste trade policy needs a comprehensive and specific analysis. Previous studies highlighted that waste import can result in illness and death to people and animals in the import nations, especially in poorer and developing nations,⁵⁰ which are the main reasons for China's waste trade ban. Besides, in the recycling stage of waste plastics, the backwardness of management level and recycling technology in some areas will lead to the regional land occupation, environmental pollution, and ecological damage, which directly brings great visual and olfactory impact, and may cause serious health risks.⁵¹ However, from the entire life cycle perspective, our research find that the import of waste PET bottles can reduce raw

polyester inputs to produce PET fibers, thus improving the PET circularity and bringing environmental benefits. Thus, it is recommended that nations should have a cautious and more comprehensive view of the plastic waste trade, and future studies on the social, environmental, and economic impacts caused by waste trade to different nations are needed.

CONCLUSION

Although the import of waste plastics caused the environmental and health burdens during the waste treatment processes, our results showed that the recycling of China's imported waste PET bottles can greatly promote global plastics circularity and bring environmental benefits. We find that China recycled 72 Mt waste PET bottles in the period 2000 to 2018. Most of these waste PET bottles was recycled to produce PET fibers, which helped save about 109 Mt oil-eq of fossil resources (e.g. coal and oil) use and avoided 233 Mt CO₂-eq emissions. We also find that despite China is the largest PET bottle recycler, its current waste PET bottles recycling technology is relatively backward and recycling model is lacking a formal and regulated waste management system.

Therefore, our study highlight that a comprehensive and specific analysis of the resource and environmental attributes based on different kinds of solid waste is needed when formulating solid waste trade policies. Besides, our results recommend that

Chinese government should develop a comprehensive formal recycling system for waste PET bottles with detailed regulations and specialized waste management organizations, and further develop the bottle-to-bottle recycling technology. After all, China as the important PET bottle producer and consumer, such development could substantially contribute to transforming China's waste PET bottle recycling system into a more effective system and thus promote the sustainable development of the global plastic circularity.

ASSOCIATED CONTENT

Supporting Information

The following files are available free of charge.

The China's PET bottles cycle construction, quantification process and data and supplementary results are listed in SI_1. (WORD)

The life cycle assessment process and data of China's PET bottles cycle are shown in SI_2. (EXCEL)

AUTHOR INFORMATION

Corresponding author:

Wei-Qiang Chen (wqchen@iue.ac.cn)

Author Contributions

All authors have given approval to the final version of the manuscript.

Notes

The authors declare no competing financial interests.

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ABBREVIATIONS

PET, Polyethylene terephthalate; MFA, Material analysis flow; LCA, Life cycle assessment

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