ACS Sustainable Chemistry & Engineering

pubs.acs.org/journal/ascecg

Research Article

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

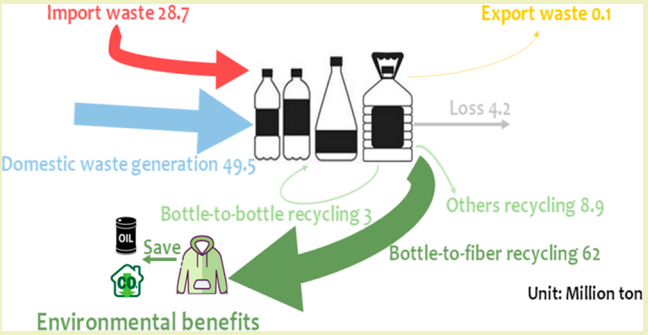
Zijie Ma, Morten W. Ryberg, Peng Wang, Linbin Tang, and Wei-Qiang Chen*

Cite This: *ACS Sustainable Chem. Eng.* 2020, 8, 16861−16868

Read Online

ACCESS | Metrics & More | Article Recommendations | Supporting Information

ABSTRACT: Polyethylene terephthalate (PET) used to account for ≈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 CO_2-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.



KEYWORDS: *PET bottle, Waste trade, Material flow analysis, Environment impact, Circular economy, Industrial ecology*

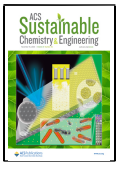
INTRODUCTION

China has been the world's largest postconsumer plastics importers since the 21st century. The import ban on all kinds of postconsumer plastics from 2018 issued by the Chinese government significantly reshaped the global structure of postconsumer plastics flow.[1] The original intention of the waste ban was to protect China's environment and human health,[2] but from the perspective of a whole life cycle, the process of 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 production[3]), has become the most favorable packaging material worldwide for water and soft drinks. China has become the largest PET bottle consumer in the world since 2010,[4] and the largest share of postconsumer plastics imported by China before 2018 is the 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 resource 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 a boom of PET production, which causes 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] it was used for metals,[17−21] waste paper,[22] and plastics,[23−26] while there is no specific research

Received: August 12, 2020
Revised: October 4, 2020
Published: November 3, 2020



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 conducted 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 bottles material flows in China. The rest of this paper is organized as follows: The Materials and Methods section explains the detailed methods and data. The Results section reveals the contributions of the 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 the Discussion section. The Conclusions section summarizes the contributions and provides policy suggestions.

MATERIALS 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 production to waste management (Figure S2), including domestic flow, waste flow, and trade flow. This part quantifies the material cycle of China's PET bottles 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 bottle process impact intensities (impacts per kilogram managed). By integrating MFA with LCA, the comprehensive analysis of resources and environmental effects of dynamics material flows can be assessed.

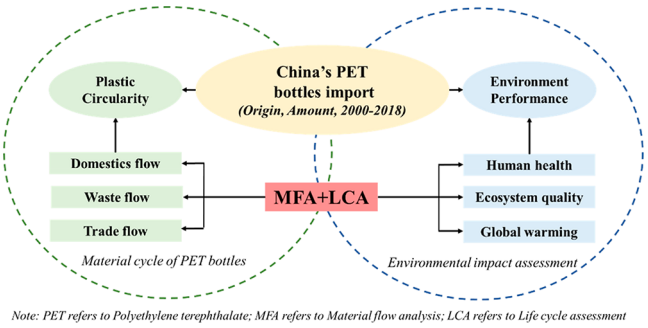


Figure 1. Research framework of material flow analysis (MFA) and life cycle assessment (LCA) of PET bottles (PET, polyethylene terephthalate; MFA, material flow analysis; LCA, life cycle assessment).

Mapping China's PET Bottle Flows along Its Life Cycle. The historic material stocks and flows along China's 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

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

where i is the index for each life stage, and j is the index for each year from 2000 to 2018. $F^{\text{input}}_{\text{PET},i,j}$ is the different forms of PET in material flows demanded by life stage i in year j. $F^{\text{import}}_{\text{PET},i,j}$ is the import of different forms of PET commodities in stage i in year j. $F^{\text{import}}_{\text{PET},i,j}$ is the export of different forms of PET commodities in stage i in year j. $F^{\text{loss}}_{\text{PET},i,j}$ is the quantity losses of PET in life stage i in year j. $F^{\text{output}}_{\text{PET},i,j}$ 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 remaining 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 ends up in 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 the 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) methodology[28] 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·yr], and 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 CO_2-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 bottles is modeled as an alternative to virgin PET production to achieve resources benefits. Hereafter, 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 modeled to substitute conventional generation of electricity and heat in China (SI 2). The generation of electricity that is used in the different life cycle processes is modeled 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

https://dx.doi.org/10.1021/acssuschemeng.0c05926
ACS Sustainable Chem. Eng. 2020, 8, 16861−16868

in China is modeled based on the International Energy Agency[32] and is used as heat input for heat consuming processes (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

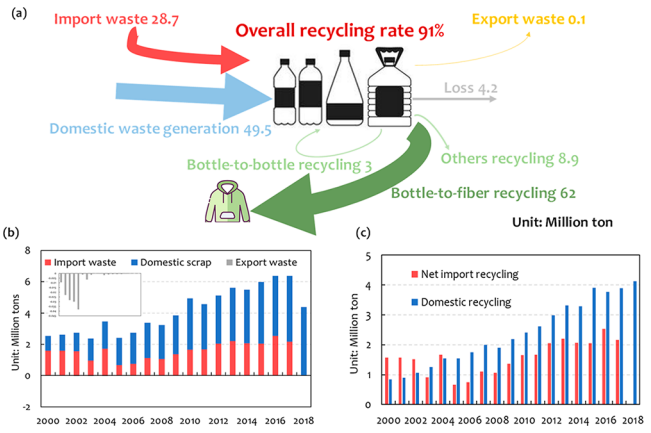


Figure 2. Flow of waste PET bottles in China 2000−2018; unit, million ton: (a) overview, (b) generation, and (c) recycling. Note that domestic recycling and net import recycling refer to the sources of recycling PET bottles that are domestically scrapped and net imported, respectively.

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 the 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 a China National Resources Recycling Association (CRRA) report,[33] only 5% of China's recycling technology applies the world's advanced recycling technology to bottle-to-bottle (BTB) recycling. These BTB recycling bottles are used to produce "nonfood contact grade" PET bottles (such as pesticide bottles), 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 the global waste plastics trade caused a huge shortage in China's recycled fiber raw material.

Contribution of Waste PET Bottles 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

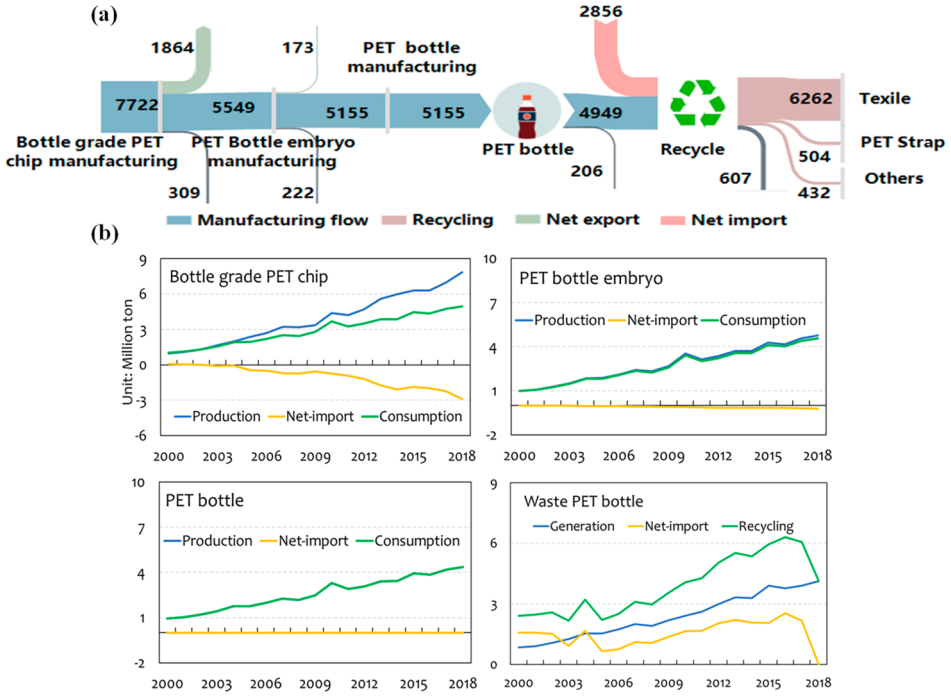


Figure 3. Material flow analysis of PET bottles in China. (a) Total amount from 2000 to 2018. All flows are accumulated to present the overall PET bottle-related products use in China during the past 19 years. The width of the edge represents the weight of each material flow in the specific temporal boundary. The color of flows differentiates the different stages in the PET bottle's life cycle. (b) Flow of each kind of PET bottle-related product.

https://dx.doi.org/10.1021/acssuschemeng.0c05926
ACS Sustainable Chem. Eng. 2020, 8, 16861−16868

assumed to be scrapped immediately after use, and thus, the amount of domestic scrapped completely comes from domestic consumption, although the increasing reliance 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 resource input. We find that 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 bottle 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% from 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.

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 4000 Eiffel Towers. The trade partners of China's waste PET bottles 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 the 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 plastic imports 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 transformed 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]

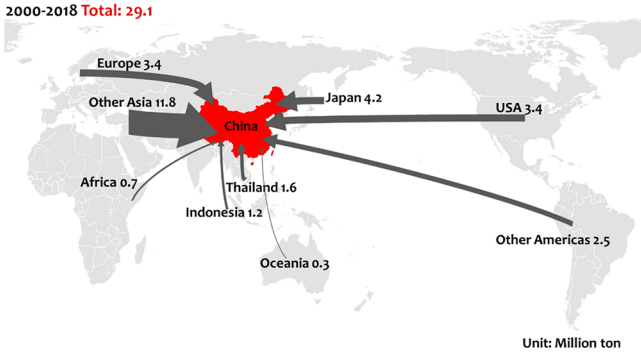


Figure 4. Direct sources of waste PET bottle imports in China from 2000 to 2018. Total amount from 2000 to 2018; unit, million ton. Arrows in each panel show the main flows of China's imports of waste PET bottles.

Environmental Performance from PET Bottles Material Cycle in China. The results of the environmental performance of PET bottle 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 (including imported bottles). Figure 5 shows the development in impacts on human health [DALY], ecosystem quality [species·yr], resources [US$2013], and global warming [CO_2-eq], which altogether indicate the impacts on the three areas of protection as well as global warming. Results for other impact categories are part of ReCiPe 2016, and all feed into one of the three areas of protection (i.e., human health, ecosystem quality, and resources, found in SI 2). About 174 Mt CO_2-eq were emitted from the PET bottle treatments (including recycling and waste disposal) in China during this period. In total, this also potentially led to 0.37 million DALY, 850 species·yr, and a loss of about 0.9 billion US$. 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 CO_2-eq between 2000 and 2018, and annual emissions of CO_2-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 of PET can save about 1.5 kg of fossil resources and avoid 3.2 kg of CO_2-eq emissions. During the 19 years, about 109 Mt oil-eq and 233 Mt CO_2-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 to 40 Mt oil-eq of fossil resources saved and 85 Mt CO_2-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 increased 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 shifts from China to other importing countries such as India.[41]

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 waste PET bottles accounted for 37% of the 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 waste PET bottles are expected to reach ~11 Mt in 2030 (Figure S6), and it will take ~6 years for the

https://dx.doi.org/10.1021/acssuschemeng.0c05926
ACS Sustainable Chem. Eng. 2020, 8, 16861−16868

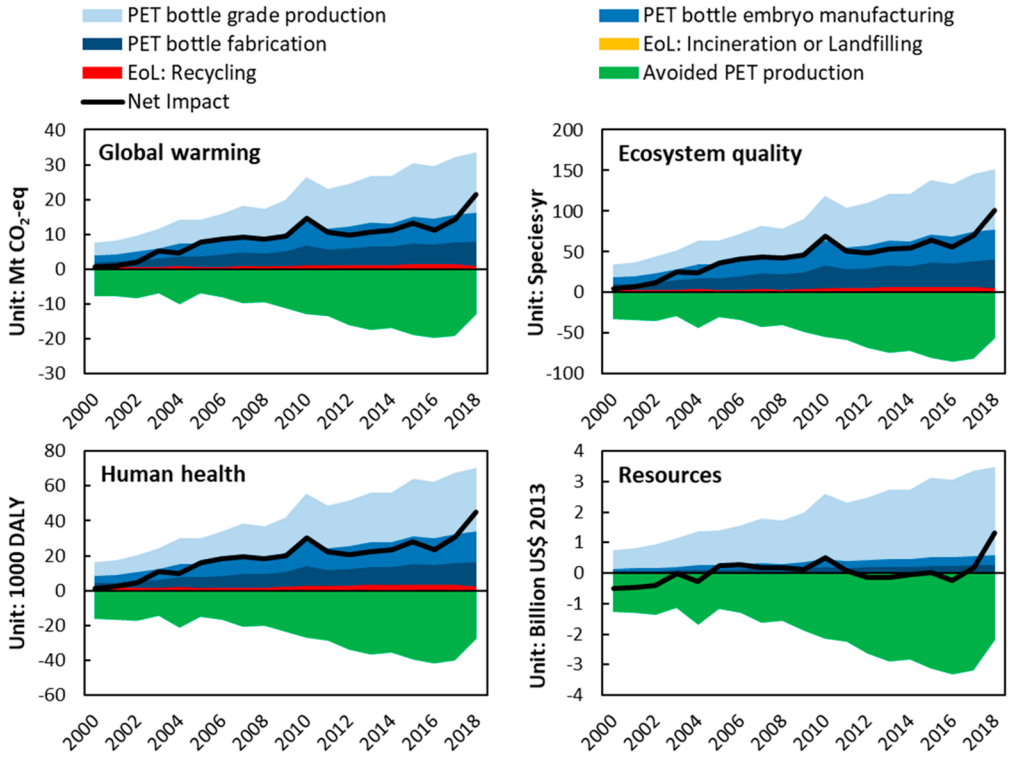


Figure 5. Temporal development in impacts on environmental impacts from production and waste management of PET bottles in China between 2000 and 2018. Environmental impacts include human health, ecosystem quality, resource costs, and global warming. Note that waste PET bottles were used to produce PET fibers that can also be produced by virgin PET. Thus, waste PET bottle recycling can reduce virgin PET production that used to produce PET fibers.

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 CO_2 emissions that contribute 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 stations[33] rather than the formal recycling chain as in the developed countries.[42] After the trade ban, the present informal PET recycling chain in China is not sustainable with the demographic transition of the cheap labor force. Also, compared to the imported plastic waste collected for treatment in waste centers, tremendous efforts are needed in the collection phase for those plastic wastes 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 the 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 recycling[12] 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 lifetime 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]

Toward a Balanced View of Solid Waste Trade. Solid waste has dual attributes of resources and hazards, and the formulation of a solid waste trade policy needs a comprehensive and specific analysis. Previous studies highlighted that waste imports 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. Also, in the recycling stage of waste plastics, the backwardness of the management level and recycling technology

https://dx.doi.org/10.1021/acssuschemeng.0c05926
ACS Sustainable Chem. Eng. 2020, 8, 16861−16868

in some areas will lead to 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 finds 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.

CONCLUSIONS

Although the import of waste plastics caused 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 from 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 CO_2-eq emissions. We also find that despite China being the largest PET bottle recycler, its current waste PET bottle recycling technology is relatively backward, and their recycling model is lacking a formal and regulated waste management system.

Therefore, our study highlights 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. Also, our results recommend that the Chinese government should develop a comprehensive formal recycling system for waste PET bottles with detailed regulations and specialized waste management organizations and further develop bottle-to-bottle recycling technology. After all, with China as an 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 sustainable development of the global plastic circularity.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acssuschemeng.0c05926.

China's PET bottle cycle construction, quantification process and data and results (PDF)

Life cycle assessment process and data of China's PET bottle cycle (XLSX)

AUTHOR INFORMATION

Corresponding Author

Wei-Qiang Chen − *Key Lab of Urban Environment and Health, Institute of Urban Environment, Chinese Academy of Sciences, Xiamen 361021, P. R. China; University of Chinese Academy of Sciences, Beijing 100049, P. R. China; Fujian Institute of Innovation, Chinese Academy of Sciences, Xiamen, Fujian 361021, P. R. China;* orcid.org/0000-0002-7686-2331; Email: wqchen@iue.ac.cn

Authors

Zijie Ma − *Key Lab of Urban Environment and Health, Institute of Urban Environment, Chinese Academy of Sciences, Xiamen 361021, P. R. China; University of Chinese Academy of Sciences, Beijing 100049, P. R. China; Fujian Institute of Innovation, Chinese Academy of Sciences, Xiamen, Fujian 361021, P. R. China*

Morten W. Ryberg − *Quantitative Sustainability Assessment Group, Sustainability Division, DTU Management, Technical University of Denmark (DTU), 2800 Kgs. Lyngby, Denmark*

Peng Wang − *Key Lab of Urban Environment and Health, Institute of Urban Environment, Chinese Academy of Sciences, Xiamen 361021, P. R. China; Fujian Institute of Innovation, Chinese Academy of Sciences, Xiamen, Fujian 361021, P. R. China*

Linbin Tang − *Key Lab of Urban Environment and Health, Institute of Urban Environment, Chinese Academy of Sciences, Xiamen 361021, P. R. China; University of Chinese Academy of Sciences, Beijing 100049, P. R. China; Fujian Institute of Innovation, Chinese Academy of Sciences, Xiamen, Fujian 361021, P. R. China*

Complete contact information is available at: https://pubs.acs.org/10.1021/acssuschemeng.0c05926

Author Contributions

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

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

This study was sponsored by the National Key Research and Development Program of Ministry of Science and Technology of China (2017YFC0505703), the Strategic Priority Research Program of Chinese Academy of Sciences (XDA23030304), and the National Natural Science Foundation of China (71961147003).

ABBREVIATIONS

PET, polyethylene terephthalate; MFA, material analysis flow; LCA, life cycle assessment

REFERENCES

(1) Pu, Y.; Wu, G.; Tang, B.; Xu, L.; Wang, B. Structural Features of Global Recycling Trade Networks and Dynamic Evolution Patterns. *Resour. Conserv. Recycl.* **2019**, *151*, 104445.

(2) Notice of the General Office of the State Council on issuing the implementation plan for prohibiting the entry of foreign waste and advancing the reform of the solid waste import administration system. http://www.gov.cn/zhengce/content/2017-07/27/content_5213738.htm (accessed Nov 1, 2019).

(3) Ryberg, M. W.; Hauschild, M. Z.; Wang, F.; Averous-Monnery, S.; Laurent, A. Global Environmental Losses of Plastics across Their Value Chains. *Resour. Conserv. Recycl.* **2019**, *151*, 104459.

(4) Zhang, H.; Wen, Z. G. The Consumption and Recycling Collection System of PET Bottles: A Case Study of Beijing, China. *Waste Manage.* **2014**, *34* (6), 987−998.

(5) Ren, Y.; Shi, L.; Bardow, A.; Geyer, R.; Suh, S. Life-Cycle Environmental Implications of China's Ban on Post-Consumer Plastics Import. *Resour. Conserv. Recycl.* **2020**, *156*, 104699.

(6) Malik, N.; Kumar, P.; Shrivastava, S.; Ghosh, S. B. An Overview on PET Waste Recycling for Application in Packaging. *Int. J. Plast. Technol.* **2017**, *21* (1), 1.

(7) Geyer, B.; Lorenz, G.; Kandelbauer, A. Recycling of Poly(Ethylene Terephthalate) - A Review Focusing on Chemical Methods. *eXPRESS Polym. Lett.* **2016**, *10* (7), 559−586.

(8) Chilton, T.; Burnley, S.; Nesaratnam, S. A Life Cycle Assessment of the Closed-Loop Recycling and Thermal Recovery of Post-Consumer PET. *Resour. Conserv. Recycl.* **2010**, *54* (12), 1241−1249.
(9) Foolmaun, R. K.; Ramjeawon, T. Life Cycle Assessment (LCA) of PET Bottles and Comparative LCA of Three Disposal Options in Mauritius. *Int. J. Environ. Waste Manage.* **2008**, *2* (1−2), 125−138.
(10) Foolmaun, R. K.; Ramjeeawon, T. Comparative Life Cycle Assessment and Social Life Cycle Assessment of Used Polyethylene Terephthalate (PET) Bottles in Mauritius. *Int. J. Life Cycle Assess.* **2013**, *18* (1), 155−171.
(11) Rochat, D.; Binder, C. R.; Diaz, J.; Jolliet, O. Combining Material Flow Analysis, Life Cycle Assessment, and Multiattribute Utility Theory: Assessment of End-of-Life Scenarios for Polyethylene Terephthalate in Tunja, Colombia Rochat et Al. Combining MFA, LCA, and MAUT. *J. Ind. Ecol.* **2013**, *17* (5), 642−655.
(12) Song, H. S.; Hyun, J. C. A Study on the Comparison of the Various Waste Management Scenarios for PET Bottles Using the Life-Cycle Assessment (LCA) Methodology. *Resour. Conserv. Recycl.* **1999**, *27* (3), 267−284.
(13) Zhang, R.; Ma, X.; Shen, X.; Zhai, Y.; Zhang, T.; Ji, C.; Hong, J. PET Bottles Recycling in China: An LCA Coupled with LCC Case Study of Blanket Production Made of Waste PET Bottles. *J. Environ. Manage.* **2020**, *260*, 110062.
(14) Shen, L.; Worrell, E.; Patel, M. K. Open-Loop Recycling: A LCA Case Study of PET Bottle-to-Fibre Recycling. *Resour. Conserv. Recycl.* **2010**, *55* (1), 34−52.
(15) Lonca, G.; Lesage, P.; Majeau-Bettez, G.; Bernard, S.; Margni, M. Assessing Scaling Effects of Circular Economy Strategies: A Case Study on Plastic Bottle Closed-Loop Recycling in the USA PET Market. *Resour. Conserv. Recycl.* **2020**, *162*, 105013.
(16) Liu, G.; Müller, D. B. Mapping the Global Journey of Anthropogenic Aluminum: A Trade-Linked Multilevel Material Flow Analysis. *Environ. Sci. Technol.* **2013**, *47* (20), 11873−11881.
(17) Chen, W. Q.; Graedel, T. E.; Nuss, P.; Ohno, H. Building the Material Flow Networks of Aluminum in the 2007 U.S. Economy. *Environ. Sci. Technol.* **2016**, *50* (7), 3905−3912.
(18) Sun, X.; Hao, H.; Zhao, F.; Liu, Z. Tracing Global Lithium Flow: A Trade-Linked Material Flow Analysis. *Resour. Conserv. Recycl.* **2017**, *124*, 50−61.
(19) Løvik, A. N.; Restrepo, E.; Müller, D. B. The Global Anthropogenic Gallium System: Determinants of Demand, Supply and Efficiency Improvements. *Environ. Sci. Technol.* **2015**, *49* (9), 5704−5712.
(20) Rasmussen, K. D.; Wenzel, H.; Bangs, C.; Petavratzi, E.; Liu, G. Platinum Demand and Potential Bottlenecks in the Global Green Transition: A Dynamic Material Flow Analysis. *Environ. Sci. Technol.* **2019**, *53*, 11541−11551.
(21) Harper, E. M.; Graedel, T. E. Illuminating Tungsten's Life Cycle in the United States: 1975−2000. *Environ. Sci. Technol.* **2008**, *42* (10), 3835−3842.
(22) Liu, M.; Tan, S.; Zhang, M.; He, G.; Chen, Z.; Fu, Z.; Luan, C. Waste Paper Recycling Decision System Based on Material Flow Analysis and Life Cycle Assessment: A Case Study of Waste Paper Recycling from China. *J. Environ. Manage.* **2020**, *255*, 109859.
(23) Nakamura, S.; Nakajima, K.; Yoshizawa, Y.; Matsubae-Yokoyama, K.; Nagasaka, T. Analyzing Polyvinyl Chloride in Japan with The Waste Input-Output Material Flow Analysis Model. *J. Ind. Ecol.* **2009**, *13* (5), 706−717.
(24) Tukker, A.; Kleijn, R.; van Oers, L.; Smeets, E. Combining SFA and LCA: The Swedish PVC Analysis. *J. Ind. Ecol.* **1997**, *1* (4), 93−116.
(25) Kuczenski, B.; Geyer, R. Material Flow Analysis of Polyethylene Terephthalate in the US, 1996−2007. *Resour. Conserv. Recycl.* **2010**, *54* (12), 1161−1169.
(26) Zhou, Y.; Yang, N.; Hu, S. Industrial Metabolism of PVC in China: A Dynamic Material Flow Analysis. *Resour. Conserv. Recycl.* **2013**, *73*, 33−40.
(27) Liu, G.; Bangs, C. E.; Müller, D. B. Unearthing Potentials for Decarbonizing the U.S. *Environ. Sci. Technol.* **2011**, *45*, 9515−9522.
(28) Huijbregts, M. A. J.; Steinmann, Z. J. N.; Elshout, P. M. F.; Stam, G.; Verones, F.; Vieira, M.; Zijp, M.; Hollander, A.; van Zelm, R. ReCiPe2016: A Harmonized Life Cycle Impact Assessment Method at Midpoint and Endpoint Level. Report I: Characterisation. *Int. J. Life Cycle Assess.* **2017**, *22*, 1−152.
(29) Verones, F.; Bare, J.; Bulle, C.; Frischknecht, R.; Hauschild, M.; Hellweg, S.; Henderson, A.; Jolliet, O.; Laurent, A.; Liao, X.; Lindner, J. P.; Maia de Souza, D.; Michelsen, O.; Patouillard, L.; Pfister, S.; Posthuma, L.; Prado, V.; Ridoutt, B.; Rosenbaum, R. K.; Sala, S.; Ugaya, C.; Vieira, M.; Fantke, P. LCIA Framework and Cross-Cutting Issues Guidance within the UNEP-SETAC Life Cycle Initiative. *J. Cleaner Prod.* **2017**, *161*, 957−967.
(30) Jolliet, O.; Margni, M.; Charles, R.; Humbert, S.; Payet, J.; Rebitzer, G.; Rosenbaum, R. IMPACT 2002+: A New Life Cycle Impact Assessment Methodology. *Int. J. Life Cycle Assess.* **2003**, *8* (6), 324−330.
(31) Zampori, L.; Pant, R. *Suggestions for Updating the Product Environmental Footprint (PEF) Method*; JRC Technical Report; European Commission, 2019. DOI: 10.2760/424613.
(32) *Electricity Generation by Source, China (People's Republic of China and Hong Kong China) 1990−2017*; IEA. https://www.eia.gov/international/analysis/country/CHN (accessed Oct 2020).
(33) *Development of Recycled PET Industry in China (In Chinese)*; CRRA, 2019.
(34) Sun, L. *Study on Effect of Processing History on Structure and Properties of Food-Grade Plastics (In Chinese)*; Hebei University of Science & Technology, 2015.
(35) GB4806.6-2016 National Food Safety Standard Plastic Resin for Food Contact (In Chinese); PRC, 2016.
(36) Qian, B. Continuous Expansion of Domestic Polyester Production Capacity (In Chinese). *Polyest. Ind.* **2013**, *27*, 34.
(37) *2016 China Chemical Industry Yearbook (In Chinese)*; CCIA, 2016; p 507.
(38) Yang, Q.; Zhang, D.; Zhou, H.; Zhang, C. Process Simulation, Analysis and Optimization of a Coal to Ethylene Glycol Process. *Energy* **2018**, *155*, 521−534.
(39) *Waste statistics: Data for 2018*. Federal Office for the Environment. https://www.bafu.admin.ch/bafu/en/home/topics/waste/state/data/abfallstatistiken-2018.html (accessed Feb 16, 2020).
(40) Wang, C.; Zhao, L.; Lim, M. K.; Chen, W. Q.; Sutherland, J. W. Structure of the Global Plastic Waste Trade Network and the Impact of China's Import Ban. *Resour. Conserv. Recycl.* **2020**, *153*, 104591.
(41) Brooks, A. L.; Wang, S.; Jambeck, J. R. The Chinese Import Ban and Its Impact on Global Plastic Waste Trade. *Sci. Adv.* **2018**, *4* (6), 1−8.
(42) Zhou, G.; Gu, Y.; Wu, Y.; Gong, Y.; Mu, X.; Han, H.; Chang, T. A Systematic Review of the Deposit-Refund System for Beverage Packaging: Operating Mode, Key Parameter and Development Trend. *J. Clean. Prod.* 2020, *251*. DOI: 10.1016/j.jclepro.2019.119660.
(43) Chen, J.; Huang, J.; Huang, X.; Sun, S.; Hao, Y.; Wu, H. How Does New Environmental Law Affect Public Environmental Protection Activities in China? Evidence from Structural Equation Model Analysis on Legal Cognition. *Sci. Total Environ.* **2020**, *714*, 136558.
(44) Tong, X.; Wang, T.; Chen, Y.; Wang, Y. Towards an Inclusive Circular Economy: Quantifying the Spatial Flows of e-Waste through the Informal Sector in China. *Resour. Conserv. Recycl.* **2018**, *135*, 163−171.
(45) Gu, Y.; Wu, Y.; Liu, J.; Xu, M.; Zuo, T. Ecological Civilization and Government Administrative System Reform in China. *Resour. Conserv. Recycl.* **2020**, *155*, 104654.
(46) Gu, A. *Network Analysis on Metabolic Structure and Metabolic Efficiency of Waste PET in Recycling (In Chinese)*; Beijing Forestry University, 2015.
(47) Welle, F. Twenty Years of PET Bottle to Bottle Recycling - An Overview. *Resour. Conserv. Recycl.* **2011**, *55* (11), 865−875.
(48) Shuai, Q. Recycling of Waste PET Plastic Beverage Bottle (In Chinese). *Sci. Technol. Innov. Her.* **2017**, No. 20, 139−140.

(49) Gu, J.; Zhang, G.; Liu, T.; Lv, L.; Li, Y.; Dong, S.; Li, H. Recycle Technology of Waste PET (In Chinese). *China Plast. Ind.* **2005**, *33* (7), 55−59.
(50) Frazzoli, C.; Orisakwe, O. E.; Dragone, R.; Mantovani, A. Diagnostic Health Risk Assessment of Electronic Waste on the General Population in Developing Countries' Scenarios. *Environ. Impact Assess. Rev.* **2010**, *30* (6), 388−399.
(51) Sevigné-Itoiz, E.; Gasol, C. M.; Rieradevall, J.; Gabarrell, X. Contribution of Plastic Waste Recovery to Greenhouse Gas (GHG) Savings in Spain. *Waste Manage.* **2015**, *46* (46), 557−567.

https://dx.doi.org/10.1021/acssuschemeng.0c05926
ACS Sustainable Chem. Eng. 2020, 8, 16861−16868