RESEARCH ARTICLE

A decision-support system for recycling of residents’ waste plastics in China based on material flow analysis and life cycle assessment

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Abstract

Recycling waste plastics is one of the important ways to save petroleum resources and reduce carbon emissions. However, the current recycling rate of waste plastics is still low. Material flow analysis can help determine the flow of waste plastics, and life cycle assessment (LCA) can be used to quantify environmental impacts. The present study integrates these two methods into the model construction of the residents’ waste plastics recycling decision-support system. This model construction is followed by sensitivity analysis of the relevant parameters affecting the performance of the waste plastics recycling system. Finally, the present study forecasts the recycling system’s performance and environmental impacts by setting four optimization scenarios based on sensitivity analysis. The results show that in 2019, a total of 8.39 million tons of high-end applications were recovered, carbon emissions during the recycling process were 34.9 million tons, and dioxin emissions were 316.11 g TEQ, with a total emission reduction of 24.47 million tons of CO₂ compared to the original production. Sensitivity analysis shows that the selection rate of waste plastic recycling, the re-sorting rate of waste plastic recycling plant, and the classification recovery rate of mixed waste had relatively high effects on the recovery performance and environmental benefits of the recycling system. In the scenario of comprehensive improvement, in 2035, the recycling volume of high-end applications will rise to 33.96 million tons, the carbon emissions will rise to 64.73 million tons, the dioxin emissions will drop to 165.98 g TEQ, and the carbon emission reduction will rise to 99.06 million tons. This study has a certain guiding role for policy-makers to formulate industry norms and related policies for waste plastic recycling.

Keywords Residents waste plastics · Material flow analysis · Life cycle assessment · Sensitivity analysis · Scenario prediction

Introduction

Along with the substantial increase in plastic usage, environmental pollution caused by waste plastics has become increasingly serious, especially that they do not easily degrade naturally (Yang et al. 2018). China produced 35 million tons of waste plastics in 2016; only 46% of these were recycled, while others were sent to landfills or were incinerated along with garbage. On the contrary, in developed states such as Japan and Germany, which have excellent waste management systems, they have very high recovery rates; in particular, Germany had attained 82% recovery in 2016 (Ke 2018). Presently, there are three ways for treating waste plastics in China: landfill, incineration, and recycling (Zhu 2011). There are many problems in the treatment of plastic waste by landfill or incineration. In landfills, plastics remain in the soil for a long time without decomposing which makes the soil unstable and may even dissolve...
the harmful substances such as stabilizers and pigments in plastics, thus resulting to secondary pollution (Guo et al. 2013). Meanwhile, energy recovery by incineration of waste plastics involves a technical link of the harmless treatment of waste gases, waste residues, and the thermal cycle process. In addition to the loss of resources caused by the incineration of waste plastics, the waste gas and waste residues produced can also pollute the environment if improperly treated (Jyothi et al. 2020). Recycling waste plastics as industrial raw materials can reduce sewage discharge by about 45% and energy consumption by 60 to 70% compared with the use of primary resources (Fang 2019; Geng and Han 2016). During the 14th Five-Year Plan period, China will further improve the entire chain of plastic pollution control system; refine the source reduction of plastic use; make arrangements for plastic waste cleaning, recycling, recycling, and scientific disposal; and promote the continuous deepening of plastic pollution control (National Development and Reform Commission & Ministry of ecological environment 2021). With the impact of global economic slowdown, the volume of industrial waste plastic recycling has decreased, while the volume of waste plastic being recycled by urban residents has increased due to garbage classification in various regions and the growth of disposable plastic consumption in China (Recycling Plastics Branch of Association 2020). Therefore, it is essential to determine the existing problems in the recycling of waste plastics in China, improve the recovery rate of waste plastics, and enhance the recycling system of waste plastics in the said country.

The processing situation of waste plastic treatment was evaluated, and the direct and potential benefits of waste plastic recycling were analyzed. Geyer et al. (2017) examined the global production, use, and recycling process of plastics and determined that as of 2015, 8.3 billion tons of plastics had been produced worldwide and a total of 6.3 billion tons of plastic waste had been generated, of which only 9% had been recycled, 12% had been incinerated, and the remaining 79% had been accumulated in landfills and the natural environment. Although waste management and infrastructure in developing countries are not perfect, the potential and benefits of waste plastic recycling are still very considerable (Hahladakis and Aljabri 2019). The recycling of waste plastics also has certain social benefits, which can be measured by the jobs provided to the society during the recycling process (Ferrão et al. 2014). The current research focuses on the reasons that affect the efficiency of waste plastic recycling. The combination of material flow analysis method and life cycle method is a commonly used research method. Nandy et al. (2015) conducted a material flow analysis (MFA) of India’s recycling of household waste plastics and discovered that 50 to 80% of waste plastics in India could be recycled, thus echoing the crucial role of the informal sector (i.e., garbage collectors, waste collectors, waste disposers, itinerant traders) and households. Van Eygen et al. (2017) presented a comprehensive quantitative analysis on waste plastic flow in Austria and concluded that a large amount of waste plastics would be accumulated in plastic products having a long product lifecycle, thus stressing the necessity to evaluate the disposal capacity and determine the priority of waste plastics in waste management. Dai and Xiao (2017) established an MFA framework of China’s plastic packaging waste to assess the metabolism of such waste. The results signified that from 2011 to 2014, the recycling volume of plastic packaging waste in China had increased by 45%, recovery rate had increased by 13%, and the output of recycled plastic products had increased by 23%. De Meester et al. (2019) established a mathematical model and assessed the economic and environmental benefits of plastics and precious metals in electronic waste by combining MFA and life cycle assessment (LCA). He noted that the most significant factor affecting the economic and environmental benefits of WEEE recycling is science and technology (mainly separation technology), while the influence of policy-based factors is not highly significant. From these studies, the influencing factors of waste plastic recycling have been generally attributed to various macro factors — including political and technical factors — without a quantitative analysis of each link of the waste plastic recycling chain. While some scholars have indeed conducted quantitative analysis, they have not focused on each link of the recycling chain from various perspectives.

MFA is a method for analyzing the material flow and storage of a specific system as defined by both time and space. It can be incorporated with LCA to systematically analyze the economic, environmental, and social benefits of a target system (Li et al. 2021). MFA’s mathematical framework is similar to a conventional chemical engineering computation. The procedure begins by generating a flow sheet diagram that represents the various processes and the flows in between. These flows are then identified and quantified, and equations — typically linear — are constructed to solve specific problems such as computing mass balances (Nandy et al. 2015). LCA can determine the environmental impact level of waste over its entire life cycle based on its functional unit on the basis of MFA, that is, MFA is classically used to prepare life cycle inventory (LCI) in LCA method (Rechberger and Brunner 2002). The current ISO standard (ISO 14040:2006) defines LCA as consisting of four interrelated components: objective and scope definition, LCI and life cycle impact assessment (LCIA), and LCA interpretation and conclusion (Wang et al. 2022). In this case, this paper focuses on the aspects of resource recovery and recycling of consumer waste plastics by Chinese residents through combining MFA and LCA. By means of a quantitative analysis of the entire recycling process and its linkages, the primary factors impacting the recycling of waste plastics can be identified. The corresponding
scenarios can be established to forecast the development and trends of China’s waste plastic recycling benefits before 2035, which can provide a decision-based support for the development of the country’s recycling system. Moreover, the combination of MFA and LCA is elaborated to acquire a better insight of the potential natural resource savings and environmental benefits of waste plastic recycling compared to a scenario without recycling, which can aid decision-makers in grasping the required information in order to clearly comprehend the current performance of waste policy implementation in such a complex situation.

Materials and methods

Mathematical framework

In this section, we will use MFA to analyze the material flow of Chinese residents’ waste plastics and combine with LCA to evaluate the recycling performance and environmental damage of residents’ waste plastic recycling systems.

System scope and objectives

Considering the proportions and significance of the sources of waste plastics in China, this paper principally studies waste plastics generated from households and from waste electrical and electronic equipment (WEEE), which are highly associated with residential consumers. In this paper, waste plastics generated from households are classified into two categories — those with high recovery value and those with low recovery value (Min 2017). The former largely refers to waste plastics with high economic value and high-efficiency recycling channels, like plastic bottles, storage box, plastic parts, and toys; meanwhile, the latter generally refers to neglected waste plastics with low economic value and low-efficiency recycling channels, like plastic bags, composite packaging, buffer packaging, and disposable tableware. The waste plastic recovery system includes four primary portions: waste plastic production, recovery process, product output, and environmental benefits. The recycling process partly concerns how waste plastics are being recycled in the system according to various treatment methods being applied by the residents. Product output denotes the output form of waste plastics after being recycled, principally including reused products, high-end applications, low-end applications, energy recovery, and material loss. The scope of this paper covers the entire reverse recycling chain, including the generation of waste plastics over a certain period (i.e., whether residents decide to discard plastic products), residents’ disposal methods, and recycling utilization. This paper’s mathematical framework can quantitatively analyze the material and energy flow of residential waste plastics under certain parameters and the environmental impact of carbon dioxide and dioxins emitted by the recycling system and estimate the carbon emission reductions of waste plastic recycling. The functional unit of LCA is defined as the treatment of 1 ton of plastic waste, to ensure the situations were comparable to each other and to assess the environmental impact of plastic waste recycling more accurately.

Construction of flow sheet and definition of parameters

Figure 1 illustrates a flow sheet of waste plastic flows from domestic source and WEEE in China. The flow begins from the moment that residents regard plastic as rubbish; that is, when they decide to discard a plastic product. There are three typical ways for consumers to deal with plastic products after they have been utilized. The choice for such treatment approaches primarily relies on both subjective and objective factors, including individual economic conditions, environmental protection consciousness, infrastructure construction, government systems, and policy guidance. There are three usual consumer choices for WEEE (China Electronics Chamber of Commerce 2016):

1. Direct recycling through formal channels
2. Transfer to relatives or friends, or remain idle at home
3. Direct discard into mixed waste

In this case, \( \zeta_{\text{EREC}} \) is the probability that residents recycle and reuse through formal channels, \( \zeta_{\text{EDON}} \) is the probability that residents transfer WEEE to their relatives and friends for use or leave them as idle at home, and \( \zeta_{\text{EMW}} \) is the probability that residents directly discard WEEE into mixed waste. Thus, the following formula can be attained:

\[
\zeta_{\text{EREC}} + \zeta_{\text{EDON}} + \zeta_{\text{EMW}} = 1
\]

Waste plastics from domestic sources are primarily classified into two categories — high recovery value and low recovery value. Meanwhile, there are three typical consumer choices for dealing with these plastics: directly discard them into mixed waste, retain for sale, or reuse (Thanh et al. 2011). For waste plastics with low recycling value, most residents tend to directly discard them into mixed waste, resulting to a bulk of wasted resources and environmental pollution. As for plastics with high recycling value, residents typically prefer to retain them for sale, while only a few of them opt to directly discard them into mixed waste (Al-Salem et al. 2009).

In this case, \( \zeta_{\text{HMW1}} \) is the probability that residents discard waste plastics of high recycling value into mixed waste, \( \zeta_{\text{HRFS1}} \) is the probability that residents choose to retain waste plastics with high recycling value for sale, and \( \zeta_{\text{HRu1}} \) is the probability that residents choose to reuse waste plastics with high recycling value. Accordingly, \( \zeta_{\text{HRM2}}, \zeta_{\text{HRFS2}}, \) and \( \zeta_{\text{HRu2}} \)
1. Reused products: refurbished WEEE
2. High-end secondary materials: recycled plastic raw materials
3. Low-end secondary materials: building materials
4. Energy: energy recovery from incineration
5. Materials lost: materials lost upon incineration or landfill treatment

Description of mathematical framework

Based on the discussed flow sheet, mathematical equations are generated to solve the mass balances. In this framework, equations are constructed in order to quantify the treated waste plastic that ends up in each particular pathway. The amount of reused household and WEEE waste plastics can be denoted as the total product reutilization (TPR).

\[
TPR = M_{\text{Twee}} * \zeta_{\text{SREC}} * \eta_{\text{Ru}} * M_{\text{THWP}} * \zeta_{\text{HRu}}
\]  

(1)

In the formula, \( M_{\text{Twee}} \) stands for WEEE waste plastic production.

The material towards high-end applications (MTHEA) can be distinguished:

\[
MTHEA = [M_{\text{Twee}} * \zeta_{\text{SREC}} * (1 - \eta_{\text{Ru}}) + (M_{\text{Twee}} * \zeta_{\text{SMW}} + M_{\text{THWP}} * \zeta_{\text{HMW}} + \epsilon_{\text{MWREC}} + M_{\text{THWP}} * \zeta_{\text{HRu}})]
\]  

(2)

In the formula, \( M_{\text{THWP}} \) represents the output of waste plastics from domestic sources, \( \eta_{\text{REC}} \) represents the plastic recycling rate of waste plastic recycling plants.

And material towards low-end applications (MTLEA):

\[
MTLEA = [M_{\text{Twee}} * \zeta_{\text{SREC}} * (1 - \eta_{\text{Ru}}) + (M_{\text{Twee}} * \zeta_{\text{SMW}} + M_{\text{THWP}} * \zeta_{\text{HMW}} + \epsilon_{\text{MWREC}} + M_{\text{THWP}} * \zeta_{\text{HRu}})]
\]  

(3)

TER (total energy recovery) represents the total amount of recovered energy. Considering the characteristics of waste plastics, landfills cannot recover energy from them; hence, this paper primarily studies recovered energy through incineration:

\[
\text{TER} = [(M_{\text{Twee}} + \zeta_{\text{SREC}} + M_{\text{THWP}} + \zeta_{\text{HMW}} + \epsilon_{\text{MWREC}} + M_{\text{THWP}} * \zeta_{\text{HRu}} + (M_{\text{Twee}} + \zeta_{\text{SMW}} + M_{\text{THWP}} * \zeta_{\text{HMW}})]
\]  

(4)

In the formula, \( \eta_{\text{INC}} \) represents the incineration efficiency of residential waste plastics, and \( CV_{\text{wp}} \) represents the calorific value of residential waste plastics. \( TP_{\text{wp}} \) represents the energy recovery rate of waste plastic incineration.

TML (total material lost) entails the overall material loss, usually from incineration and landfill treatment. MLI is the material loss caused by incineration, while MLLF is the material loss resulting from landfills. TML is the sum of MLI and MLLF.
will also exacerbate the greenhouse effect. This study mainly uses the IPCC method to assess the carbon emissions of the residential waste plastic recycling system, as shown in formula (8) (Sevigné-Itoiz et al. 2015). In addition, this study uses the life cycle method to compare the carbon emissions from the recycling of waste plastics with the carbon emissions of the equivalent plastic produced from crude oil to calculate the carbon emission reduction effect of recycling, as shown in formula (9):

\[ CE = \left[ M_{\text{Tweee}} \times \epsilon_{\text{SINC}} \times (1 - \eta_{\text{H}}) + (M_{\text{Tweee}} \times \epsilon_{\text{EMW}} + M_{\text{THWP}} \times \epsilon_{\text{HWM}}) \times \epsilon_{\text{MWINC}} \times \epsilon_{\text{Ru}} \right] \times \frac{EF_{wpr}}{\eta_{\text{REC}}} \times \eta_{\text{REC}} \times \frac{EF_{\text{upr}}}{1} \]  \\
\[ CR = \left[ M_{\text{Tweee}} \times \epsilon_{\text{SINC}} \times (1 - \eta_{\text{H}}) + (M_{\text{Tweee}} \times \epsilon_{\text{EMW}} + M_{\text{THWP}} \times \epsilon_{\text{HWM}}) \times \epsilon_{\text{MWINC}} \times \epsilon_{\text{Ru}} \right] \times \frac{EF_{wpr}}{\eta_{\text{REC}}} \times \eta_{\text{REC}} \times \frac{EF_{\text{upr}}}{1} \]  

Dioxin compounds can cause greater harm to human health and have a persistent presence in the environment (Zhan et al. 2016). The dioxins produced by the incineration of waste plastic are mainly discharged into fly ash and the atmosphere, and the dioxin discharged into the fly ash flows to landfill after being harmless and stabilized. In this study, the emission factor estimation method was used to estimate the dioxin emission from waste plastic incineration:

\[ DE = \left[ (M_{\text{Tweee}} \times \epsilon_{\text{SINC}} \times \epsilon_{\text{Ru}} + M_{\text{THWP}} \times \epsilon_{\text{HWM}}) \times \epsilon_{\text{MWINC}} \times \epsilon_{\text{Ru}} \right] \times \frac{EF_{d}}{(1 - \eta_{\text{H}}) + (M_{\text{Tweee}} \times \epsilon_{\text{EMW}} + M_{\text{THWP}} \times \epsilon_{\text{HWM}}) \times \epsilon_{\text{MWINC}} \times \epsilon_{\text{Ru}}} \times \frac{EF_{\text{upr}}}{(1 - \eta_{\text{REC}}) \times \eta_{\text{REC}}} \times \frac{1}{(EF_{pp} - EF_{upr})} \]

In the above formula, \( DE \) stands for the amount of dioxins emitted from the incineration of waste plastics to the atmosphere, in \( \mu g \) TEQ/t (United Nations Environment Programme Division 2005).

### Description of case study and data inventory

#### Overview of recycling of waste plastics in China in 2019

China’s production of waste plastics in its various industries in 2019 is shown in Table 1. Around 63 million tons of waste plastics were produced by seven major industries — building materials, cars, fisheries, industrial packaging, textiles, households, and electrical and electronic equipment (Ke 2018; Recycling Plastics Branch of Association 2020). From this total, 32.445 million tons of waste plastics were generated by domestic source. Around 13.205 million tons of high recovery value and 19.24 million tons of low recovery value accounted for 51.5% of the overall waste plastics produced in China in 2019. WEEE produced 4.41 million tons of waste plastics, equivalent 7%. The proportion of WEEE and domestic source was as high as 58.5%. The two components were highly associated with and considerably significant to the consumers and denoted a huge proportion of the total value. Thus, research on this subset of waste plastics is vital for enhancing the recycling of waste plastics in China.

#### Data inventory

This study intends to take waste plastic recycling from domestic sources and WEEE in China in 2019 as a representative case for quantitative analysis. Due to the fact that the data for the process in this study come from a variety of sources, MFA is used to achieve mass balance in the research system. The parameters pertaining to the recycling process of waste plastics in China and the 2019 values are presented in Table 2. For WEEE, 52.09% of consumers opted to recycle, while up to 44.21% of consumers intended to transfer such waste to relatives and friends or leave them as idle at home. Around 3.7% of the consumers directly

| Industries          | Waste plastic production in 2019 (10,000 tons) | Data sources                                      |
|---------------------|-----------------------------------------------|--------------------------------------------------|
| Building materials  | 472.5                                         | Ke (2018); Recycling Plastics Branch of Association (2020) |
| Automobile          | 315                                           | Recycling Plastics Branch of Association (2020)   |
| Agriculture and fisheries | 252                                      | Recycling Plastics Branch of Association (2020)   |
| Industrial packing  | 630                                           | Ke (2018); Recycling Plastics Branch of Association (2020) |
| Textile             | 525                                           | Ke (2018); Recycling Plastics Branch of Association (2020) |
| Domestic sources    | 3244.5                                        | Ke (2018); Recycling Plastics Branch of Association (2020) |
| WEEE                | 441                                           | Recycling Plastics Branch of Association (2020)   |
| Total               | 6300                                          | Recycling Plastics Branch of Association (2020)   |
discarded them into mixed waste (China Electronics Chamber of Commerce 2016; Li et al. 2021). Regarding waste plastics generated from domestic sources, 69% with high recovery value were retained for sale, 27% of the residents directly discarded them into mixed waste, and 4% intended to reuse them. In contrast, residents were more likely to render improper choices for waste plastics with low recovery value: 28% of the residents retained them for sale, 64% chose to directly discard them into mixed waste, and 8% reused them in households (Thanh et al. 2011). When mixed waste was picked up by the street recyclers, approximately 3.7% of waste plastics would flow into the waste plastic market for a relatively efficient secondary sorting (Editorial Board Of Statistics 2020). Approximately 63% of these plastics were further broken down, recycled, and processed into recycled plastics, with the rest being incinerated for energy recovery or landfill treatment as the prevailing waste treatment methods in China. Around 40% of the remaining products were incinerated, and 60% were landfilled (Recycling Plastics Branch of Association 2020). Incineration efficiency was approximately 75%, while 25% of the mass remained as bottom ash and fly ash. Bottom ash accounted for 22%, which could be utilized for building as a low-end application of plastics; fly ash accounted for 3%, which required ash treatment prior to landfilling (Yao 2014).

### Results analysis

#### Base year analysis

The recycling situation for waste plastics by Chinese residents in 2019 is presented in Table 3. In 2019, for every ton of residential plastic waste, about 0.14 tons were reused,
transferred or left idle, and about 0.34 tons of recycled plastic (high-end and low-end applications) were recovered, with an energy recovery of about $2.42 \times 10^3$ MJ. Under the current recycling system, 0.47 tons of waste plastics are still lost due to incineration and landfill. In terms of environmental impact, carbon dioxide emission is about 0.95 tons per ton of residential plastic waste recycling, while dioxin emission due to incineration is about 8.58 µg TEQ. Moreover, waste plastic recycling can achieve carbon emission reduction of about 0.66 tons, which shows that waste plastic recycling can save resources at the same time, but also produce good environmental benefits. Overall, 8.39 million tons of high-end applications were recovered, with a recovery rate of approximately 23%, and 3.68 million tons of low-end applications were recovered. The energy recovery is $8.9 \times 10^{10}$ MJ, and the total material loss during the recovery process is approximately 17.2 million tons. Combining the life cycle, this study calculates that the carbon emissions of the recycling system are approximately 34.9 million tons. Compared with the original production volume, carbon emissions have been reduced by 24.5 million tons, and the amount of dioxin emitted from the incineration of waste plastics into the atmosphere is 316.11 g TEQ. This study also used e-sankey 4.0 software to draw the material flow chart of waste plastic recycling of Chinese residents in 2019, as shown in Fig. 2. The figure depicts the recycling process of three different types of residential waste plastics: WEEE waste plastics, high recycling value waste plastics, and low recycling value waste plastics. More than 70% of WEEE waste plastics are resold to consumers as second-hand products, given to others or left at home, while high and low recycling value waste plastics are mainly sold to recyclers or directly discarded into mixed waste. In the end, only 24% of high and low recycling value waste plastics are recycled for high-end applications.

### Sensitivity analysis

Sensitivity analysis is a somewhat uncertain quantitative analysis technology for examining the influence of certain changes in relevant factors on a specific or a group of key indicators. Its essence is to explain the law of key indicators

| Output index | Output value per ton | Total numerical value |
|--------------|----------------------|-----------------------|
| Total Product Recovery (TPR) | 0.03 (t) | 1148.6 (kt) |
| High end application (MTHEA) | 0.23 (t) | 8390.0 (kt) |
| Low end application (MTLEA) | 0.11 (t) | 4076.6 (kt) |
| Energy recovery (TER) | $2.42 \times 10^3$ (MJ) | $8.90 \times 10^{10}$ (MJ) |
| Lost (TML) | 0.47 (t) | 17,199.6 (kt) |
| Reuse of waste plastics from domestic sources | 0.06 (t) | 2067.4 (kt) |
| Transfer or idle of waste plastics from WEEE sources | 0.05 (t) | 1949.7 (kt) |
| Carbon emissions (CE) | 0.95 (t) | 34,904.8 (kt) |
| Carbon reduction (CR) | 0.66 (t) | 24,473.6 (kt) |
| Dioxin emissions (DE) | 8.6 (µg TEQ) | 316.1 (g TEQ) |

Fig. 2  Material flow of Chinese residents’ waste plastic recycling system in 2019
as influenced by the changes of these factors through changing the values of the relevant variables one-by-one (Frey and Patil 2002). By analyzing the internal and external environments of the overall waste plastic recycling chain, it can be determined that the primary macro factors affecting waste plastic recycling include consumer behavior, technology, and government policies (Knickmeyer 2020). Therefore, this part conducts sensitivity analysis on the main factors influencing the recycling efficiency of waste plastics in China from the perspectives of consumer behavior, technology, and government policies. It also identifies the key linkages of waste plastic recycling to provide decision-making support. In addition, it conducts a sensitivity analysis for environmental benefit improvement — that is, the impact of the improvement of each key link of the recycling chain for carbon dioxide and dioxin emissions. In this study, all parameters that are under control of consumers, policy, or technology are tested towards their importance. Limited to the length of this article, the sensitivity analysis diagrams and tables are not shown in the main text. Tables 8, 9, 10, 11, 12, 13, 14, 15, 16, 17 and 18 in the appendix shows the changes in indicators such as material recycling and environmental damage corresponding to every increase of a certain percentage of parameter strength on the basis of residents’ waste plastic recycling in 2019.

- **Consumer behavior:** $\xi_{\text{EREC}}$, $\zeta_{\text{HKFS1}}$, $\zeta_{\text{HKFS2}}$
- **Technological progress:** $\eta_{\text{Ru}}$, $\eta_{\text{SREC}}$, $\eta_{\text{REC}}$, $TP_{wp}$
- **Government policy:** $\epsilon_{\text{MWREC}}$, $\epsilon_{\text{MWINC}}$, $\epsilon_{\text{SINC}}$

### Parameters related to consumer behavior

Consumer behavior entails the type of treatment that residents prefer to adopt when waste plastic is produced — that is, whether they choose to recycle it through regular channels, discard it as domestic waste, or reuse it (Yin et al. 2014). This study conducted a quantitative analysis of the influence of consumers on the disposal tendency of WEEE and domestic waste plastics. Sensitivity analysis found that both the recycling performance and environmental benefits of recycling systems increased significantly with the increase in the selection rate of waste plastic recycling. In particular, for every 1% increase in the WEEE recycling selection rate ($\xi_{\text{EREC}}$), the TPR recycling rate increases by 1.9%; for every 5% increase in the recycling selection rate of high-value waste plastics ($\zeta_{\text{HKFS1}}$), the MTHEA recycling rate and CR both increase by 3.9%, and the DE decreases by 2.3%. For every 5% increase in the recycling selection rate of low-value waste plastics ($\zeta_{\text{HKFS2}}$), the recovery rates of MTHEA and CR both increase by 5.7%, while DE decreases by 3.3%. On the one hand, whether one deems WEEE or waste plastics from households, formal recycling channels need to be adopted instead of discarding them into mixed waste. On the other hand, waste plastics with a high recycling value have a relatively high economic value and high-efficiency recycling methods; hence, more residents intend to recycle them. Meanwhile, waste plastics with a low recycling value tend to be discarded into mixed waste rather than recycled. In contrast, sensitivity analysis determines that waste plastics with low recycling values are a significant yet neglected factor. These plastics have a more ample effect on the conservation of environment, especially when they are kept for sale or discarded into mixed waste.

### Parameters related to technological progress

Technology-related parameters denote the increase in utilization rates for each recycling link due to scientific and technological progress, thus influencing the material recovery and environmental benefits (Fernandes et al. 2021). Based on sensitivity analysis results, for every 5% increase in $\eta_{\text{Ru}}$, the TPR recovery rate increases by 10%; for every 5% increase in $TP_{wp}$, the TER recovery rate increases by 19.1%; for every 1% increase in $\eta_{\text{REC}}$, the MTHEA recovery rate and CR both increase by 1.2%. Obviously, the classification refurbishment rate ($\eta_{\text{Ru}}$), plastic recycling efficiency ($\eta_{\text{REC}}$), and waste plastic incineration energy recovery rate ($TP_{wp}$) has a direct impact on the amount of material recycling, and the increase in waste plastic recycling efficiency has a significant carbon emission reduction effect. The increase in the re-sorting rate ($\eta_{\text{SREC}}$) has a significant impact on the amount of recycled plastics recycled and carbon reductions for every 5% increase in $\eta_{\text{SREC}}$: the MTHEA recovery rate and CR both increase by 7.9%. Increasing incineration efficiency ($\eta_{\text{INC}}$) can not only increase energy production for every 5% increase in $\eta_{\text{INC}}$, the TER recovery rate increase by 5%, but also reduce material loss caused by landfills. However, affected by the energy recovery rate of waste plastic incineration, the increase in energy production is bound to cause more energy loss. The increase of $\eta_{\text{SREC}}$ and $\eta_{\text{INC}}$ will also cause a slight increase in carbon emissions. This is due to the energy consumption of waste plastics originally flowing to landfills in the process of turning to recycling. However, technological progress can effectively achieve carbon and dioxin emission reduction and reduce material losses, thereby significantly improving the performance and environmental benefits of the entire recycling system.

### Parameters related to government policy

Parameters pertaining to government decision-making refer to the government establishing relevant policies for the regulation of recycling waste plastics and guiding waste plastic treatments (Tsai et al. 2020). These parameters generally include the three treatments for mixed waste: recycling, incineration, and landfill. Recycling of mixed waste has a relatively high impact on material recycling and environmental
benefits. When $\epsilon_{MWREC}$ increases by 5% and $\epsilon_{MWLF}$ decreases by 5%, the MTHEA recovery rate and CR both increase by 4.9%. When $\epsilon_{MWREC}$ increases by 5% and $\epsilon_{MWINC}$ decreases by 5%, MTHEA recovery rate and CR both increase by 3.8%, and CE and DE decreased by 2% and 7% respectively. Presently, waste plastics in the recycling of mixed waste mostly rely on street recyclers and pickers; picking efficiency is very low, and most recyclable materials are lost to incineration or landfill of mixed wastes, thus resulting to much wasted resources (Jin 2021). Thus, this linkage has a potential for substantial improvement, as the government can employ relevant measures such as garbage classification to actively guide recycling of waste plastics in mixed waste. When $\epsilon_{SINC}$ increases by 5% and $\epsilon_{SLF}$ decreases by 5%, TEP recovery rate increases by 2.9%. When $\epsilon_{MWINC}$ increases by 5% and $\epsilon_{MWLF}$ decreases by 5%, TEP recovery rate increases by 7.6%. Compared to incineration, landfill treatment of waste plastics can pose serious problems involving resource waste and environmental pollution (Wei 2016). However, due to relatively low costs, there are still a large proportion of waste plastics that end up in landfills, after which they become permanent waste. The additives in plastics pollute the soil and water resources and occupy much valuable land resources. In this case, the government should implement approaches for reducing the proportion of landfill treatment and promoting mixed waste flow for incineration treatment.

**Scenario prediction**

**Forecast for the residents’ waste plastics output in China**

Based on survey statistics, first, determine the annual increase rate of waste plastics, and then use the amount of waste plastics generated in a certain year as the base annual output to calculate the amount of waste plastics generated in a certain year in the future (Rouzi 2009). With the limitations imposed by economic progress and population factors, the amount of waste plastics being produced by various industries is relatively stable; it is approximately equal to the overall amount of waste plastics, multiplied by the proportions of various industries (Ke 2018). Therefore, we have the following formulas for predicting the production of waste plastics in various industries:

$$M_{WPi} = M_{WP} \times (1 + r)^t \times \epsilon_i$$  \hspace{1cm} (11)

$M_{WPi}$ represents the amount of waste plastics in each industry in year $t$, $M_{WP}$ represents the total amount of waste plastics in the base year, and $\epsilon_i$ represents the proportion of various industries; $r$ represents the annual increasing rate of waste plastic output.

The prediction formula of this study has higher requirements for the prediction scenario, and the key lies in the determination of $r$. Luan (2020) uses the logistics model to simulate the development trend of waste plastics in the
future based on the statistical data from 1949 to 2018, assuming that after 2020, the average annual growth rate of GDP is about 5% and the population growth rate is about 2%; the average annual growth rate of waste plastics is about 2.5%. The forecast results are presented in Table 4.

Scenario prediction of residents’ waste plastic recycling in China in the future

In the sensitivity analysis in the third section, there are three primary factors influencing the economic and environmental benefits of China’s waste plastic recycling systems: consumer behavior, technology, and government policy. In this section, relatively significant attributes, such as the residents’ willingness to recycle, the initial sorting rate of mixed waste, and the re-sorting rate of waste plastic factories, are considered, and the influence of these factors on the recycling system of waste plastics in China is deliberated. The setting of parameters is primarily based on the existing economic and technological development levels and the implementation of policies in China, and development status of waste recycling in developed nations, through encompassing the three levels involving residents, technology, and the government. Moreover, the formulation and implementation of laws and regulations, such as Measures for Solid Waste Management, Regulations on Pollution Prevention and Control of Waste Plastics Processing and Utilization, and Regulations on Environmental Protection and Management of Imported Waste Plastics, have been systematically considered in this paper. Predictions of the performance and environmental benefits of recycling systems continue until 2035. The scenario prediction parameters set up in this study are shown in Table 5.

**Scenario 1** Residents’ environmental protection awareness has been increased, and their willingness to recycle has been gradually enhanced. The latter is a vital component for improving recycling efficiency. Some studies have discussed the incentive mechanism and the influencing factors of residents’ recycling willingness in China. Relying on the pace of China’s economic development and urbanization process, Qiao (2017) interviewed and investigated various residents and scrutinized the impact of environmental awareness, policies and regulations, and incentive mechanisms on the residents’ classification behavior. Based on the planned behavior theory, the A-B-C theory, and a questionnaire survey, Hu and Yu (2012) examined the recycling intentions of e-waste consumers and the factors influencing them. The present paper comprehensively considers the above factors and provides a scientific prediction on the enhancement of the residents’ desire to recover and its benefits.

**Scenario 2** The initial sorting rate for mixed refuse has gradually increased and all mixed waste after re-sorting flows to incineration. De Meester et al. (2019) implemented MFA and LCA of precious metals and plastics on electronic and electrical equipment; the results indicated that separation rate was the most vital factor for enhancing recovery efficiency. On March 2017, an implementation plan for domestic garbage classification system was officially released. The said program required that by the end of 2020, relevant laws, regulations, and standardized systems for garbage classification should be fundamentally established, and a replicable and extensible classification model for domestic waste should be formulated. The “Shanghai Municipal Implementation Plan on Further Strengthening the Treatment of Plastic Pollution” clearly stated that by 2022, Shanghai will fully realize the goal of zero landfill of plastic waste (Shanghai Development and Reform Commission 2020). Therefore, this study predicts the initial sorting rate of mixed waste in China’s residential plastic recycling system based on the comprehensive consideration of the specific implementation of policies in China and the situation of waste plastic disposal in developed countries.

**Scenario 3** Alongside the development of science and technology, the re-sorting rate of waste plastics recycling plants has gradually increased. Liu et al. (2014) used the cyclone method to sort waste plastic films of different densities, laying a foundation for further processing of plastic waste in China. In most

| Table 5 Scenario setting |
|--------------------------|
| **Scenario 1: Consumer behavior** |
| $\xi_{EREC}$ | 0.5209 | 0.5259 | 0.5309 | 0.5359 | 0.5409 | 0.5459 | 0.5469 | 0.5479 | 0.5489 | 0.5499 | 0.55 | 0.55 | 0.55 |
| $\xi_{HKFS1}$ | 0.69 | 0.71 | 0.73 | 0.75 | 0.77 | 0.79 | 0.8 | 0.81 | 0.82 | 0.83 | 0.84 | 0.85 | 0.9 |
| $\xi_{HKFS2}$ | 0.28 | 0.33 | 0.38 | 0.43 | 0.48 | 0.53 | 0.58 | 0.61 | 0.64 | 0.67 | 0.7 | 0.73 | 0.8 |
| **Scenario 2: Government policy** |
| $\varepsilon_{MWREC}$ | 0.037 | 0.187 | 0.337 | 0.487 | 0.637 | 0.707 | 0.733 | 0.753 | 0.763 | 0.773 | 0.783 | 0.793 | 0.8 |
| $\varepsilon_{SINC}$ | 0.4 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **Scenario 3: Technological progress** |
| $\eta_{SREC}$ | 0.63 | 0.67 | 0.71 | 0.75 | 0.77 | 0.79 | 0.81 | 0.82 | 0.83 | 0.84 | 0.85 | 0.86 | 0.9 |
| **Scenario 4: Comprehensive improvement (Combination of scenarios 1–3)** |

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countries, the separation technology of waste plastics is mostly focused on the use of controlled wind separation, a combination of wind separation and other methods, or a hydrocyclone separation method (Shi et al. 2016). Fu et al. (2017) assessed the economic and environmental benefits of waste plastic recycling in China under a mechanized recycling scenario and has provided vital information for China’s current waste plastic recycling industry. Hence, this paper comprehensively considers the application of mechanization sorting and other innovative sortation technologies in waste plastic recycling plants according to China’s development of its waste plastic recycling systems, and thus predicted the improvement of re-selecting efficiency of the recycling system in the future.

Scenario 4  Basing upon the residents’ increased preferences for recycling, the classification and recycling of waste plastics has become standardized, and the initial sorting rate of mixed waste has gradually improved.

Table 6 predicts the development trend of waste plastic recycling per ton of residents based on four different scenarios. Based on the four scenarios, the recycled plastic recycling and carbon reduction displacement per ton of residents have increased year by year, and the loss of material loss has decreased year by year. Scenario 1 shows that when residents gradually choose to recycle waste plastics instead of discarding waste plastic, the economic benefits of the waste plastic recycling system will also increase. The increase in residents’ willingness to recycling reduces the incineration and landfill of scrap plastic per ton, which has led to the decline in TER and DE of the waste plastic recycling system and the rise of the CE. Under the guidance of government policies (scenario 2), waste plastic landfilling is gradually eliminated and waste plastic incineration is minimized, which makes TER, CE, and DE evolve in an inverted “U” shape. Scenario 3 shows that the improvement of sorting technology in waste plastic recycling plants reduces the incineration and landfill of waste plastics, which leads to the decrease of TER and DE and the increase of CE in waste plastic recycling system. With the improvement of residents’ awareness of recycling, the implementation of policies, and technological progress (scenario 4), the economic and environmental benefits of the waste plastic recycling system have been significantly improved. By 2035, 0.62 tons of MTHEA and 0.16 tons of MTLEA per ton of waste plastics were recycled, and the TER generated by incineration was reduced to $8.54 \times 10^5$ MJ, and the TML caused by incineration and landfill dropped to 0.06 tons. CE and DE were reduced to 1.18 tons and 3 μg TEQ, respectively. Compared with the initial production of plastic raw materials, per ton of waste plastic flowing into the recycling system can achieve a carbon emission reduction of 1.81 tons. Moreover, the increase of waste plastic recycling leads to the increase of energy consumption of the recycling system, while the reduction of incineration leads to the reduction of carbon emissions, which makes the carbon dioxide emissions of the recycling system show an inverted U evolution. Therefore, the recycling of household waste plastics can significantly improve the economic benefits of the recycling system, while minimizing environmental damage.

This study calculated the total change trend of recycling indicators based on the predictive output of residents’ waste plastic, as shown in Table 7. The recycling rate of household waste plastics and the environmental benefits brought by recycling continue to improve, that is, with the increase of waste volume, TPR, MTHEA, MTLEA, and CR in the four scenarios have a significant growth effect. In particular, the recovery benefit of scenario 4 is the most obvious. By 2035, 33,960.3 kilotons of MTHEA and 8498.5 kilotons of MTLEA will be recovered, and 99,062.3 kilotons of carbon dioxide emission reduction can be achieved. In addition to the downward trend of TML in scenario 4, the other two scenarios show a U change trend, and the change trend of dioxin emissions also shows similar results, which shows that simple residents’ recycling willingness, policy guidance or technological progress cannot minimize material loss or environmental damage. Moreover, with the development of scenario 4, carbon emissions have gradually stabilized, which is in line with China’s target to achieve carbon peak by 2035. It is crucial to improve the recycling efficiency of the waste plastic system, whether accomplished by improving residents’ recycling willingness, standardizing waste classification and recycling, or enhancing re-sorting efficiency.

The rates of increase in recovery benefits as ranked from highest to lowest are as follows: scenario 4, scenario 1, scenario 3, and scenario 2. Compared to the standardization of garbage classification and recycling and the increase of re-sorting rate of waste plastic, the recovery benefit delivered through increasing residents’ recycling is greater. It should be noted that the residents’ recycling awareness should be improved and that their recycling intention should be enhanced. Since the recovery benefit is the greatest in scenario 4, with an increased willingness among the residents to recycle, simultaneously improving waste plastic classification and recycling can increase recovery benefit by a greater extent. Moreover, if the re-sorting rate of waste plastics can be further increased, recovery benefit can be more rapidly improved. In this case, one should not ignore vital factors, such as standardizing garbage classification and the recycling and re-sorting rates, while elevating the residents’ preferences for recycling. It is indeed necessary to stimulate the balanced growth of various factors to enhance the recycling system for waste plastics in China and to improve recycling efficiency. This paper draws the material flow diagram of the residential waste plastic recycling system in 2035 in the scenario of the comprehensive development of the recycling system, as shown in Fig. 3.
Table 6 Scenario prediction of per ton residents’ waste plastic recycling

| Scenario  | Total Product Recovery (TPR) | High end application (MTHEA) | Low end application (MTLEA) | Energy recovery (TER) | Lost (TML) | Carbon emissions (CE) | Carbon reduction (CR) | Dioxin emissions (DE) |
|-----------|------------------------------|------------------------------|------------------------------|-----------------------|------------|-----------------------|----------------------|----------------------|
|           | Unit                         | 2020                        | 2021                        | 2022                  | 2023       | 2024                  | 2025                  | 2030                 | 2035         |
| Scenario 1| t                            | 0.03                        | 0.03                        | 0.03                   | 0.03       | 0.03                  | 0.03                  | 0.03                 | 0.03         |
|           | t                            | 0.24                        | 0.26                        | 0.28                   | 0.29       | 0.31                  | 0.33                  | 0.37                 | 0.40         |
|           | t                            | 0.11                        | 0.11                        | 0.11                   | 0.11       | 0.12                  | 0.12                  | 0.12                 | 0.12         |
|           | MJ                           | 2.31*10^3                   | 2.21*10^3                   | 2.10*10^3             | 2.00*10^3  | 1.89*10^3             | 1.80*10^3             | 1.50*10^3           | 1.33*10^3 |
|           | t                            | 0.45                        | 0.44                        | 0.42                   | 0.40       | 0.39                  | 0.38                  | 0.33                 | 0.31         |
|           | t                            | 0.95                        | 0.95                        | 0.95                   | 0.95       | 0.95                  | 0.95                  | 0.95                 | 0.96         |
|           | t                            | 0.71                        | 0.76                        | 0.81                   | 0.86       | 0.91                  | 0.95                  | 1.09                 | 1.17         |
|           | μg TEQ                       | 8.2                         | 7.8                         | 7.5                    | 7.1        | 6.7                   | 6.4                   | 5.3                  | 4.7          |
| Scenario 2| t                            | 0.03                        | 0.03                        | 0.03                   | 0.03       | 0.03                  | 0.03                  | 0.03                 | 0.03         |
|           | t                            | 0.26                        | 0.30                        | 0.33                   | 0.36       | 0.38                  | 0.40                  | 0.40                 | 0.40         |
|           | t                            | 0.14                        | 0.15                        | 0.16                   | 0.16       | 0.17                  | 0.17                  | 0.17                 | 0.17         |
|           | MJ                           | 3.26*10^3                   | 3.28*10^3                   | 3.30*10^3             | 3.32*10^3  | 3.34*10^3             | 3.31*10^3             | 3.17*10^3           | 3.15*10^3 |
|           | t                            | 0.38                        | 0.34                        | 0.30                   | 0.26       | 0.24                  | 0.23                  | 0.22                 | 0.22         |
|           | t                            | 1.21                        | 1.26                        | 1.32                   | 1.38       | 1.41                  | 1.41                  | 1.40                 | 1.40         |
|           | t                            | 0.76                        | 0.86                        | 0.96                   | 1.06       | 1.10                  | 1.12                  | 1.16                 | 1.16         |
|           | μg TEQ                       | 11.6                        | 11.7                        | 11.7                   | 11.8       | 11.9                  | 11.7                  | 11.2                 | 11.2         |
| Scenario 3| t                            | 0.03                        | 0.03                        | 0.03                   | 0.03       | 0.03                  | 0.03                  | 0.03                 | 0.03         |
|           | t                            | 0.24                        | 0.26                        | 0.27                   | 0.28       | 0.29                  | 0.29                  | 0.31                 | 0.33         |
|           | t                            | 0.11                        | 0.11                        | 0.12                   | 0.12       | 0.12                  | 0.12                  | 0.12                 | 0.12         |
|           | MJ                           | 2.36*10^3                   | 2.30*10^3                   | 2.24*10^3             | 2.21*10^3  | 2.18*10^3             | 2.15*10^3             | 2.07*10^3           | 2.01*10^3 |
|           | t                            | 0.45                        | 0.44                        | 0.42                   | 0.42       | 0.41                  | 0.40                  | 0.38                 | 0.37         |
|           | t                            | 0.96                        | 0.96                        | 0.97                   | 0.98       | 0.98                  | 0.98                  | 0.99                 | 1.00         |
|           | t                            | 0.71                        | 0.75                        | 0.79                   | 0.81       | 0.83                  | 0.85                  | 0.91                 | 0.95         |
|           | μg TEQ                       | 8.4                         | 8.2                         | 7.9                    | 7.8        | 7.7                   | 7.6                   | 7.4                  | 7.1          |
| Scenario 4| t                            | 0.03                        | 0.03                        | 0.03                   | 0.03       | 0.03                  | 0.03                  | 0.03                 | 0.03         |
|           | t                            | 0.29                        | 0.36                        | 0.42                   | 0.47       | 0.51                  | 0.53                  | 0.58                 | 0.62         |
|           | t                            | 0.14                        | 0.15                        | 0.15                   | 0.16       | 0.16                  | 0.16                  | 0.16                 | 0.16         |
|           | MJ                           | 3.04*10^3                   | 2.77*10^3                   | 2.46*10^3             | 2.23*10^3  | 2.03*10^3             | 1.81*10^3             | 1.22*10^3           | 8.54*10^2 |
|           | t                            | 0.36                        | 0.29                        | 0.23                   | 0.18       | 0.15                  | 0.13                  | 0.09                 | 0.06         |
|           | t                            | 1.20                        | 1.24                        | 1.26                   | 1.29       | 1.29                  | 1.27                  | 1.22                 | 1.18         |
|           | t                            | 0.85                        | 1.05                        | 1.23                   | 1.38       | 1.47                  | 1.54                  | 1.71                 | 1.81         |
|           | μg TEQ                       | 10.8                        | 9.8                         | 8.7                    | 7.9        | 7.2                   | 6.4                   | 4.3                  | 3.0          |
| Scenario | Total Product Recovery (TPR) | High end application (MTHEA) | Low end application (MTLEA) | Energy recovery (TER) | Lost (TML) | Carbon emissions (CE) | Carbon reduction (CR) | Dioxin emissions (DE) |
|----------|------------------------------|-----------------------------|-----------------------------|----------------------|------------|----------------------|----------------------|-----------------------|
| Scenario 1 | kt 1188.6 1229.9 1272.5 1316.5 1361.9 1398.5 1519.2 1591.2 1800.3 | kt 9230.4 10107.5 11022.7 11977.4 12973.0 13929.7 18079.3 21937.3 | kt 4213.3 4354.3 4499.7 4649.6 4804.2 4960.2 5743.6 6583.1 | MJ 8.73*10^10 8.54*10^10 8.34*10^10 8.12*10^10 7.89*10^10 7.69*10^10 7.30*10^10 | kt 17042.8 16867.3 16762.5 16457.3 16221.0 16044.9 16020.8 16767.6 | kt 35802.4 36722.9 37667.2 38635.7 39629.0 40654.2 46132.5 52271.9 | kt 26925.0 29483.6 32153.4 34938.2 37842.1 40632.9 52737.2 63991.0 | g TEQ 309.97 303.33 296.17 288.45 280.17 273.23 258.02 259.35 |
| Scenario 2 | kt 1177.3 1206.7 1236.9 1267.8 1299.5 1332.0 1507.0 1705.1 | kt 9873.9 11426.8 13051.2 14749.6 15774.7 16418.9 19228.9 21841.9 | kt 5268.9 5701.6 6152.6 6622.6 6952.4 7138.4 8045.2 9098.3 | MJ 1.23*10^11 1.27*10^11 1.31*10^11 1.35*10^11 1.39*10^11 1.41*10^11 1.53*10^11 1.72*10^11 | kt 14538.1 13276.8 11943.3 10534.9 9957.1 9981.1 10824.2 12184.7 | kt 45586.6 48967.9 52489.8 56157.2 58812.5 60726.8 67581.0 76380.3 | kt 28802.2 33332.0 38070.3 43024.6 46014.8 47894.0 56090.8 63712.8 | g TEQ 437.59 451.31 465.45 480.01 495.22 501.81 543.88 612.20 |
| Scenario 3 | kt 1177.3 1206.7 1236.9 1267.8 1299.5 1332.0 1507.0 1705.1 | kt 9145.8 9934.1 10756.1 11319.0 11903.3 12509.8 15023.7 17772.9 | kt 4238.6 4406.1 4579.3 4726.1 4877.4 5033.3 5790.8 66387.6 | MJ 8.90*10^10 8.89*10^10 8.88*10^10 8.87*10^10 8.86*10^10 8.85*10^10 9.18*10^10 1.00*10^11 | kt 17074.7 16932.8 16773.1 16893.6 17009.7 17121.0 18483.0 20108.1 | kt 36085.4 37303.1 38559.2 39688.9 40851.1 42046.5 48064.5 54826.5 | kt 26678.2 28977.7 31375.5 33017.5 34721.9 36491.0 43834.7 51901.7 | g TEQ 316.02 315.73 315.23 318.81 322.35 325.91 355.95 391.15 |
| Scenario 4 | kt 1188.6 1229.9 1272.5 1316.5 1361.9 1398.5 1519.2 1591.2 1800.3 | kt 11066.1 13876.7 16787.4 19295.6 21087.0 22575.3 28277.2 33960.3 | kt 5307.7 5724.2 6101.9 6463.0 6694.5 6829.7 7594.5 8498.5 | MJ 1.15*10^11 1.07*10^11 9.76*10^10 9.09*10^10 8.46*10^10 7.73*10^10 5.92*10^10 4.67*10^10 | kt 13489.8 11230.3 8983.0 7141.8 6092.8 5521.1 4277.2 3426.7 | kt 45375.8 47982.2 50182.2 52430.3 53755.7 54320.5 58854.6 64729.0 | kt 32279.7 40478.3 48968.8 56180.4 61492.5 65852.1 82484.6 99062.3 | g TEQ 407.30 381.13 346.56 322.80 300.49 274.58 210.32 165.98 |
Discussion

De Meester et al. (2019) deemed that the most significant factor influencing the economic and environmental benefits of recycling is science and technology — mainly separation technology — while the impact of policy factors is not relatively significant. Ke (2018) believed that the three fundamental factors that impact recovery rate are the mature recycling industry chain, the degree of implementation of plastic recycling by the consumers, and the healthy operation of recycling plants. The results depicted that the primary problems influencing the recycling of waste plastics emerge in terms of technical level and consumer behavior. The efficiency of waste plastic sorting and separation is low, resulting to much waste plastics with mixed waste flow into incineration and landfill facilities. Moreover, due to the limitations of the existing thermal cycle technology, and the stability of incineration system and equipment, a lower incineration efficiency causes losses of energy (Tang et al. 2017). Thus, it is highly significant to enhance both the initial sorting rate of mixed waste and the re-sorting rate of waste plastic recycling plants. Moreover, consumers lack consciousness in classification and recycling; several volumes of waste plastics are either idle, not fully recycled, or directly discarded, bringing forth much trouble in waste plastic recycling. One of the most prominent problems concern the low recycling value of waste plastics such as plastic bags; due to its imperfect recycling channels, most residents opt to directly discard them, yielding resource waste and environmental pollution. Finally, a huge proportion of waste plastics are sent to landfills, leading to resource losses to a certain extent.

Although technical parameters such as initial sorting rate and re-sorting rate of mixed waste have a significant influence on enhancing the recycling efficiency of waste plastics, this is based on a certain amount of recycling. In particular, when the residents’ willingness to recycle is not high, the increase of recycling benefits will be insignificant even if the technical parameters and other factors have improved a lot. For instance, recycling willingness of e-waste is low; most of them remain idle or transferred, and only a small portion flows into recycling systems (Afroz et al. 2013). Hence, the most vital approach is to elevate the recycling willingness of Chinese residents, especially those concerning waste plastic with relatively low recycling values. Simultaneously, a classified recycling of waste plastics should be implemented, and the sorting rate in recycling plants should be improved so as to maximize the advantages of recycling waste plastics in China.

Conclusions and recommendations

This paper has introduced how to express an MFA with mathematical properties and associated with LCA as an equation framework, which is beneficial to utilizing more forward-looking decision support. Although the said approach is retrospective, it can be effective for assessing the potential impacts of certain decisions. For instance, it can highlight the improvement aspects to bring forth the greatest benefits in waste plastic recycling, thus helping achieve recycling
goals. Applying a combination of MFA and LCA, this study assesses the reverse logistics process of WEEE and waste plastic recycling among Chinese urban households and identifies the parameters for each link in the process. Sensitivity analysis was implemented to point out the key factors for progressing the waste plastic recycling system in China, after which the recovery benefits and environmental damages upon the improvement of each key link were reasonably predicted.

The three most significant factors in the improvement of waste plastic recycling systems in China are the consumers' recycling willingness, the initial sorting rate of mixed waste, and the re-sorting rate of waste plastic recycling plants. The improvement of these factors can enhance the economic and environmental advantage of waste plastic recycling. Under the comprehensive improvement scenario, the recycling rate of recycled plastic materials increased from 25.9 to 62%, the carbon emission reduction was increased by about 4 times, and the dioxin emission was reduced by nearly 1/2.

The Chinese government has played an important role in recycling waste plastics. At the source of recycling, the government can formulate policies to guide consumers to properly handle waste plastics and urge consumers to classify waste plastics to improve residents' awareness of recycling. In the process of recycling, the government can formulate laws and regulations to regulate mixed waste recycling to improve the initial sorting rate and encourage waste plastic recycling plants to improve the re-sorting rate through policy subsidies, so as to improve the recycling benefits of waste plastics. In particular, the government should guide the recycling of waste plastic or the energy recovery by incineration, in order to mitigate the proportion of direct abandonment or landfill, especially for plastics with low recycling values. In response to the increasing scale of China's plastic metabolism, policies such as plastic bag ban, levy relevant taxes, and introduce incentive mechanism can be used to restrict the use of plastic products, especially disposable plastic products. Meanwhile, by strengthening the supervision of the overall life cycle of plastics, the volume of waste plastics entering the environment at each stage can be mitigated, consequently reducing the waste of resources and environmental pollution. In addition, the calculation of carbon emission does not take into account the transport process and other links, which can be further discussed.

Appendix A: sensitivity analysis results.

1. Parameters related to consumer behavior.

Table 8  Sensitivity analysis of the waste plastic recycling selection rate from WEEE sources

| WEEE to Recycle (ζERECC) | Unit | 0.5209 | 0.5259 | 0.5309 | 0.5359 | 0.5409 | 0.5459 |
|--------------------------|------|--------|--------|--------|--------|--------|--------|
| Total Product Recovery (TPR) | kt   | 1148.6 | 1159.6 | 1170.6 | 1181.7 | 1192.7 | 1203.7 |
| High end application (MTHEA) | kt   | 8390.0 | 8395.3 | 8400.5 | 8405.8 | 8411.1 | 8416.4 |
| Low end application (MTLEA) | kt   | 4076.6 | 4075.7 | 4074.7 | 4073.8 | 4072.8 | 4071.9 |
| Energy recovery (TER) | MJ   | 8.90*10^10 | 8.89*10^10 | 8.89*10^10 | 8.88*10^10 | 8.87*10^10 | 8.86*10^10 |
| Lost (TML) | kt   | 17,199.6 | 17,186.1 | 17,172.6 | 17,159.1 | 17,145.6 | 17,132.1 |
| Carbon emissions (CE) | kt   | 34,904.8 | 34,893.2 | 34,881.5 | 34,869.9 | 34,858.2 | 34,846.5 |
| Carbon reduction (CR) | kt   | 24,473.6 | 24,489.0 | 24,504.4 | 24,519.8 | 24,535.1 | 24,550.5 |
| Dioxin emissions (DE) | g    | 316.11 | 315.82 | 315.53 | 315.24 | 314.95 | 314.66 |

Table 9  Sensitivity analysis of the waste plastic recycling selection rate from domestic source (high recovery value)

| High recovery value waste plastic to keep for sale (ζHKFS) | Unit | 0.69 | 0.74 | 0.79 | 0.84 | 0.89 | 0.94 |
|----------------------------------------------------------|------|------|------|------|------|------|------|
| Total Product Recovery (TPR) | kt   | 1148.6 | 1148.6 | 1148.6 | 1148.6 | 1148.6 | 1148.6 |
| High end application (MTHEA) | kt   | 8390.0 | 8718.5 | 9046.9 | 9375.4 | 9703.9 | 10,032.3 |
| Low end application (MTLEA) | kt   | 4076.6 | 4095.4 | 4114.2 | 4133.0 | 4151.8 | 4170.5 |
| Energy recovery (TER) | MJ   | 8.90*10^10 | 8.70*10^10 | 8.50*10^10 | 8.29*10^10 | 8.09*10^10 | 7.90*10^10 |
| Lost (TML) | kt   | 17,199.6 | 16,898.6 | 16,597.5 | 16,296.5 | 15,995.5 | 15,694.4 |
| Carbon emissions (CE) | kt   | 34,904.8 | 34,943.6 | 34,962.9 | 34,982.3 | 35,001.6 | 35,001.6 |
| Carbon reduction (CR) | kt   | 24,473.6 | 25,431.7 | 26,389.9 | 27,348.0 | 28,306.1 | 29,264.3 |
| Dioxin emissions (DE) | g    | 316.11 | 308.89 | 301.67 | 294.45 | 287.23 | 280.01 |
### Table 10  Sensitivity analysis of the waste plastic recycling selection rate from domestic source (low recovery value)

| Low recovery value waste plastic to keep for sale ($\zeta_{HKFS}$) | Unit | 0.28 | 0.33 | 0.38 | 0.43 | 0.48 | 0.53 |
|---------------------------------------------------------------|------|------|------|------|------|------|------|
| Total Product Recovery (TPR)                                  | kt   | 1148.6 | 1148.6 | 1148.6 | 1148.6 | 1148.6 | 1148.6 |
| High end application (MTHEA)                                  | kt   | 8390.0 | 8686.6 | 9347.2 | 9825.7 | 10,304.3 | 10,782.9 |
| Low end application (MTLEA)                                  | kt   | 4076.6 | 4104.0 | 4131.4 | 4158.7 | 4186.1 | 4213.4 |
| Energy recovery (TER)                                         | MJ   | $8.90 \times 10^{10}$ | $8.61 \times 10^{10}$ | $8.31 \times 10^{10}$ | $8.01 \times 10^{10}$ | $7.72 \times 10^{10}$ | $7.42 \times 10^{10}$ |
| Lost (TML)                                                    | kt   | 17,199.6 | 16,761.0 | 16,322.4 | 15,883.8 | 15,445.1 | 15,006.5 |
| Carbon emissions (CE)                                         | kt   | 34,904.8 | 34,933.0 | 34,961.2 | 34,989.5 | 35,017.7 | 35,045.9 |
| Carbon reduction (CR)                                         | kt   | 24,473.6 | 25,869.6 | 27,265.7 | 28,661.7 | 30,057.7 | 31,453.7 |
| Dioxin emissions (DE)                                         | g    | 316.11 | 305.59 | 295.07 | 284.55 | 274.03 | 263.52 |

### Table 11  Sensitivity analysis of the classification refurbishment rate

| Classification refurbishment rate ($\eta_{Ru}$) | Unit | 0.50 | 0.55 | 0.60 | 0.65 | 0.70 | 0.75 |
|------------------------------------------------|------|------|------|------|------|------|------|
| Total Product Recovery (TPR)                      | kt   | 1148.6 | 1263.4 | 1378.3 | 1493.2 | 1608.0 | 1722.9 |
| High end application (MTHEA)                      | kt   | 8390.0 | 8330.7 | 8271.3 | 8212.0 | 8152.7 | 8093.3 |
| Low end application (MTLEA)                       | kt   | 4076.6 | 4060.2 | 4043.8 | 4027.4 | 4010.9 | 3994.5 |
| Energy recovery (TER)                             | MJ   | $8.90 \times 10^{10}$ | $8.89 \times 10^{10}$ | $8.87 \times 10^{10}$ | $8.86 \times 10^{10}$ | $8.84 \times 10^{10}$ | $8.83 \times 10^{10}$ |
| Lost (TML)                                       | kt   | 17,199.6 | 17,163.8 | 17,128.0 | 17,092.1 | 17,056.3 | 17,020.5 |
| Carbon emissions (CE)                             | kt   | 34,904.8 | 34,776.6 | 34,648.4 | 34,520.2 | 34,392.0 | 34,263.7 |
| Carbon reduction (CR)                             | kt   | 24,473.6 | 24,300.5 | 24,127.4 | 23,954.4 | 23,781.3 | 23,608.2 |
| Dioxin emissions (DE)                             | g    | 316.11 | 315.60 | 315.09 | 314.58 | 314.07 | 313.56 |

### Table 12  Sensitivity analysis of the re-sorting rate

| Sorting to waste plastic plant ($\eta_{SREC}$) | Unit | 0.63 | 0.68 | 0.73 | 0.78 | 0.83 | 0.88 |
|------------------------------------------------|------|------|------|------|------|------|------|
| Total Product Recovery (TPR)                    | kt   | 1148.6 | 1148.6 | 1148.6 | 1148.6 | 1148.6 | 1148.6 |
| High end application (MTHEA)                    | kt   | 8390.0 | 9055.9 | 9721.7 | 10,387.6 | 11,053.5 | 11,719.4 |
| Low end application (MTLEA)                     | kt   | 4076.6 | 4149.9 | 4223.1 | 4296.3 | 4369.5 | 4442.7 |
| Energy recovery (TER)                           | MJ   | $8.90 \times 10^{10}$ | $8.63 \times 10^{10}$ | $8.35 \times 10^{10}$ | $8.08 \times 10^{10}$ | $7.80 \times 10^{10}$ | $7.53 \times 10^{10}$ |
| Lost (TML)                                      | kt   | 17,199.6 | 16,522.9 | 15,846.2 | 15,169.4 | 14,492.7 | 13,816.0 |
| Carbon emissions (CE)                           | kt   | 34,904.8 | 35,280.3 | 35,655.8 | 36,031.3 | 36,406.8 | 36,782.3 |
| Carbon reduction (CR)                           | kt   | 24,473.6 | 26,416.0 | 28,358.3 | 30,300.7 | 32,243.0 | 34,185.4 |
| Dioxin emissions (DE)                           | g    | 316.11 | 306.37 | 296.62 | 286.88 | 277.13 | 267.39 |
### Table 13  Sensitivity analysis of the incineration efficiency

| Incineration efficiency ($\eta_{Inc}$) | Unit | 0.75  | 0.80  | 0.85  | 0.90  | 0.95  | 1.00  |
|---------------------------------------|------|-------|-------|-------|-------|-------|-------|
| Total Product Recovery (TPR)          | kt   | 1148.6| 1148.6| 1148.6| 1148.6| 1148.6| 1148.6|
| High end application (MTHEA)          | kt   | 8390.0| 8390.0| 8390.0| 8390.0| 8390.0| 8390.0|
| Low end application (MTLEA)           | kt   | 4076.6| 3622.3| 3167.9| 2713.6| 2259.2| 1804.9|
| Energy recovery (TER)                 | MJ   | 8.90*10^10 | 9.50*10^10 | 1.01*10^11 | 1.07*10^11 | 1.13*10^11 | 1.19*10^11|
| Lost (TML)                            | kt   | 17,199.6| 17,519.1| 17,838.6| 18,158.1| 18,477.5| 18,797.0|
| Carbon emissions (CE)                 | kt   | 34,904.8| 36,353.7| 37,802.5| 39,251.3| 40,700.2| 42,149.0|
| Carbon reduction (CR)                 | kt   | 24,473.6| 24,473.6| 24,473.6| 24,473.6| 24,473.6| 24,473.6|
| Dioxin emissions (DE)                 | g    | 316.11 | 316.11 | 316.11 | 316.11 | 316.11 | 316.11|

### Table 14  Sensitivity analysis of the recycling efficiency of waste plastics

| Recycling efficiency of waste plastics ($\eta_{Rec}$) | Unit | 0.82  | 0.825 | 0.83  | 0.835 | 0.84  | 0.845 |
|-----------------------------------------------------|------|-------|-------|-------|-------|-------|-------|
| Total Product Recovery (TPR)                        | kt   | 1148.6| 1148.6| 1148.6| 1148.6| 1148.6| 1148.6|
| High end application (MTHEA)                        | kt   | 8390.0| 8441.2| 8492.3| 8543.5| 8594.6| 8645.8|
| Low end application (MTLEA)                         | kt   | 4076.6| 4026.5| 3976.4| 3926.2| 3876.1| 3826.0|
| Energy recovery (TER)                               | MJ   | 8.90*10^10 | 8.90*10^10 | 8.90*10^10 | 8.90*10^10 | 8.90*10^10 | 8.90*10^10|
| Lost (TML)                                           | kt   | 17,199.6| 17,198.6| 17,197.6| 17,196.5| 17,195.5| 17,194.5|
| Carbon emissions (CE)                               | kt   | 34,904.8| 34,985.2| 35,065.5| 35,145.8| 35,226.1| 35,306.4|
| Carbon reduction (CR)                               | kt   | 24,473.6| 24,622.8| 24,772.1| 24,921.3| 25,070.5| 25,219.8|
| Dioxin emissions (DE)                               | g    | 316.11 | 316.11 | 316.11 | 316.11 | 316.11 | 316.11|

### Table 15  Sensitivity analysis of the energy recovery rate of waste plastic incineration

| Energy recovery rate of waste plastic incineration ($TP_{wp}$) | Unit | 0.256  | 0.306  | 0.356  | 0.406  | 0.456  | 0.506  |
|---------------------------------------------------------------|------|--------|--------|--------|--------|--------|--------|
| Total Product Recovery (TPR)                                  | kt   | 1148.6 | 1148.6 | 1148.6 | 1148.6 | 1148.6 | 1148.6 |
| High end application (MTHEA)                                  | kt   | 8390.0 | 8390.0 | 8390.0 | 8390.0 | 8390.0 | 8390.0 |
| Low end application (MTLEA)                                   | kt   | 4076.6 | 4076.6 | 4076.6 | 4076.6 | 4076.6 | 4076.6 |
| Energy recovery (TER)                                         | MJ   | 8.90*10^10 | 1.06*10^11 | 1.24*10^11 | 1.41*10^11 | 1.59*10^11 | 1.76*10^11|
| Lost (TML)                                                    | kt   | 17,199.6| 16,804.5| 16,409.3| 16,014.2| 15,619.1| 15,223.9|
| Carbon emissions (CE)                                         | kt   | 34,904.8| 34,904.8| 34,904.8| 34,904.8| 34,904.8| 34,904.8|
| Carbon reduction (CR)                                         | kt   | 24,473.6| 24,473.6| 24,473.6| 24,473.6| 24,473.6| 24,473.6|
| Dioxin emissions (DE)                                         | g    | 316.11 | 316.11 | 316.11 | 316.11 | 316.11 | 316.11|
Table 16  Sensitivity analysis of the mixed waste sorting rate

| Mixed waste to classification recovery ($\epsilon_{MWREC}$) | Unit 0.037 | 0.087 | 0.137 | 0.187 | 0.237 | 0.287 | 0.337 | 0.387 | 0.437 |
|----------------------------------------------------------|------------|-------|-------|-------|-------|-------|-------|-------|-------|
| Total Product Recovery (TPR)                             | kt         |       |       |       |       |       |       |       |       |
| High end application (MTHEA)                             | kt         | 8390.0| 8804.4| 9218.7| 9633.1|10,047.5|10,461.8|10,876.2|11,290.6|
| Low end application (MTLEA)                              | kt         | 4076.6| 4191.4| 4306.1| 4420.8| 4535.6| 4477.4| 4419.2| 4361.0|
| Energy recovery (TER) (MJ)                              |            |       |       |       |       |       |       |       |       |
| Lost (TML)                                               | kt         | 17,199.6| 16,647.7| 16,095.8| 15,543.9| 14,992.0| 14,767.1| 14,542.1| 14,317.2|
| Carbon emissions (CE)                                    | kt         | 34,904.8| 35,800.2| 36,695.6| 37,591.0| 38,486.4| 37,727.5| 36,968.6| 36,209.6|
| Carbon reduction (CR)                                    | kt         | 24,473.6| 25,682.3| 26,891.0| 28,099.7| 29,308.5| 30,517.2| 31,725.9| 32,934.6|
| Dioxin emissions (DE)                                    | g          | 316.11 | 319.67 | 323.23 | 326.79 | 330.36 | 309.85 | 289.35 | 268.85 |
Table 17  Sensitivity analysis of the incineration rate of mixed waste after re-sorting

| Mixed waste in waste plastic market to incineration ($S_{INC}$) | Unit | 0.4   | 0.45  | 0.5   | 0.55  | 0.6   | 0.65  |
|---------------------------------------------------------------|------|-------|-------|-------|-------|-------|-------|
| Total Product Recovery (TPR) kt                              |      | 1148.6| 1148.6| 1148.6| 1148.6| 1148.6| 1148.6|
| High end application (MTHEA) kt                             |      | 8390.0| 8390.0| 8390.0| 8390.0| 8390.0| 8390.0|
| Low end application (MTLEA) kt                               |      | 4076.6| 4141.4| 4206.2| 4271.0| 4335.8| 4400.5|
| Energy recovery (TER) MJ                                     |      | 8.90*10^10| 9.16*10^10| 9.41*10^10| 9.66*10^10| 9.92*10^10| 1.02*10^11|
| Lost (TML) kt                                                |      | 17,199.6| 17,077.1| 16,954.7| 16,832.2| 16,709.7| 16,587.3|
| Carbon emissions (CE) kt                                     |      | 34,904.8| 35,524.5| 36,144.2| 36,763.9| 37,383.6| 38,003.3|
| Carbon reduction (CR) kt                                     |      | 24,473.6| 24,473.6| 24,473.6| 24,473.6| 24,473.6| 24,473.6|
| Dioxin emissions (DE) g                                      |      | 316.11 | 325.12 | 334.14 | 343.15 | 352.16 | 361.18 |

Table 18  Sensitivity analysis of the incineration rate of mixed waste after sorting

| Mixed waste to incineration ($S_{MWINC}$)   | Unit | 0.507 | 0.557 | 0.607 | 0.657 | 0.707 | 0.757 |
|---------------------------------------------|------|-------|-------|-------|-------|-------|-------|
| Total Product Recovery (TPR) kt              |      | 1148.6| 1148.6| 1148.6| 1148.6| 1148.6| 1148.6|
| High end application (MTHEA) kt              |      | 8390.0| 8390.0| 8390.0| 8390.0| 8390.0| 8390.0|
| Low end application (MTLEA) kt               |      | 4076.6| 4249.6| 4422.5| 4595.4| 4768.4| 4941.3|
| Energy recovery (TER) MJ                     |      | 8.90*10^10| 9.58*10^10| 1.03*10^11| 1.09*10^11| 1.16*10^11| 1.23*10^11|
| Lost (TML) kt                                |      | 17,199.6| 16,872.7| 16,545.7| 16,218.8| 15,891.9| 15,564.9|
| Carbon emissions (CE) kt                     |      | 34,904.8| 36,559.2| 38,213.5| 39,867.9| 41,522.2| 43,176.6|
| Carbon reduction (CR) kt                     |      | 24,473.6| 24,473.6| 24,473.6| 24,473.6| 24,473.6| 24,473.6|
| Dioxin emissions (DE) g                      |      | 316.11 | 325.17 | 340.17 | 364.24 | 388.30 | 412.36 | 436.43 |
| Abbreviations | Variables and abbreviations |
|---------------|----------------------------|
| MFA           | Material flow analysis     |
| LCA           | Life cycle assessment      |
| LCI           | Life cycle inventory       |
| LCIA          | Life cycle impact assessment|
| WEEE          | Waste electrical and electronic equipment |
| TPR           | Total product reutilization|
| MTHEA         | Material towards high-end applications |
| MTLEA         | Material towards low-end applications |
| TER           | Total energy recovery      |
| TML           | Total material lost        |
| MLI           | Material loss caused by incineration |
| MLLF          | Material loss resulting from landfills |
| GHG           | Greenhouse gas emissions   |
| GWP           | Global warming potential   |
| CE            | Carbon emissions           |
| CR            | Carbon emission reduction  |
| DE            | Dioxin emission            |
| CE EDON       | WEEE to Recycle            |
| CE HMW        | WEEE to Discard or idle    |
| CE HMW2       | High recovery value to Discard to mixed waste |
| CE HKFS2      | Low recovery value waste plastic to keep for sale |
| CE HRu2       | Low recovery value waste plastic to reuse |
| CE HRu1       | High recovery value to reuse |
| CE HRu2       | Low recovery value waste plastic to reuse |
| CE HRu1       | High recovery value to reuse |
| CE HMW        | WEEE to Discard to mixed waste |
| CE HKFS1      | High recovery value waste plastic to keep for sale |
| ζEREC         | WEEE to Recycle            |
| ζEDON         | WEEE to Transfer or idle   |
| ζHMW          | WEEE to Discard to mixed waste |
| ζHMW2         | High recovery value to Discard to mixed waste |
| ζHKFS2        | Low recovery value waste plastic to keep for sale |
| ζHRu2         | Low recovery value waste plastic to reuse |
| ζHRu1         | High recovery value to reuse |
| ηBA           | Incineration to bottle ash |
| ηFA           | Incineration to fly ash    |
| ηREC          | Recycling efficiency of waste plastics |
| ηSINC         | Mixed waste to incineration |
| ηSLF          | Mixed waste in waste plastic plant to landfill |
| ηLA           | Classification refurbishment rate |
| ηSINC         | Mixed waste in waste plastic plant to incineration |
| ηFA           | Incineration to fly ash    |
| ηSINC         | Mixed waste in waste plastic plant to incineration |
| ηFA           | Incineration to fly ash    |
| ηREC          | Recycling efficiency of waste plastics |
| ηSINC         | Mixed waste in waste plastic plant to incineration |
| ηFA           | Incineration to fly ash    |
| ηREC          | Recycling efficiency of waste plastics |
| ηSINC         | Mixed waste in waste plastic plant to incineration |
| ηFA           | Incineration to fly ash    |
| ηREC          | Recycling efficiency of waste plastics |
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| ηREC          | Recycling efficiency of waste plastics |
| ηSINC         | Mixed waste in waste plastic plant to incineration |
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Declarations

Ethics approval and consent to participate We all declare that manuscript reporting studies do not involve any human participants, human data, or human tissue. So, it is not applicable in this section.

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