A Decision-support System for Recycling of Residents' Waste Plastics in China Based on Material Flow Analysis and Life Cycle Assessment

MANZHI LIU (liumanzhi@cumt.edu.cn)
China University of Mining and Technology https://orcid.org/0000-0003-4533-8489
Jixin Wen
China University of Mining and Technology
Linlin Zhang
China University of Mining and Technology
Jixin Wu
China University of Mining and Technology
Xiaotao Yang
China University of Mining and Technology
Ying Qin
China University of Mining and Technology
Yingjie Liu
China University of Mining and Technology

Research Article

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Posted Date: December 16th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-1098791/v1

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Manzhi Liu*, Jixin Wen, Linlin Zhang, Jixin Wu, Xiaotao Yang, Ying Qin, Yingjie Liu

School of Economics and Management, China University of Mining and Technology, Xuzhou 221116, China

liumanzhi@cumt.edu.cn(M. –Z, Liu); TS20070074A31@cumt.edu.cn(J. –X, Wen); zhanglinlin09133@163.com(L. –L, Zhang); 1989859084@qq.com(J. –X, Wu); TS21070070A31@cumt.edu.cn(X. –T, Yang); 2083727420@qq.com(Y., Qin); 1194010433@qq.com(Y. –J, Liu)

* Corresponding author: Manzhi Liu: Tel.: +86 13512563912, E-mail: liumanzhi@cumt.edu.cn (M.-Z, Liu).

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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, 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. 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 research has a certain guiding role for policy makers to formulate industry norms and related policies for waste plastic recycling.

Keywords: Waste plastics; Material flow analysis; Life cycle assessment; Sensitivity analysis; Scenario prediction

1. 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 and

Ministry of ecological environment, 2021). 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 an 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 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.

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, 2019). 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 decisionmakers in grasping the required information in order to clearly comprehend the current performance of waste policy implementation in such a complex situation.

2. Materials and methods

2.1 Mathematical framework

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., 2010). 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). In the following, 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.

2.1.1 System scope and objectives

China's waste plastics primarily originate from building materials, automobiles, textiles, agriculture and fisheries, industrial packaging, residents' daily life and durable goods, among all other sources (Ke,2018). 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. Recycling value denotes the recycling capacity of waste materials; it is usually determined by various factors, such as the original value of products, recycling rate and recycling channels(Min, 2017). In this paper, waste plastics generated from households are classified into two categories – those with high recovery value, and those with low recovery value. The former largely refers to waste plastics with high economic value and high-efficiency recycling channels, like plastic bottles, storage box, Plastic parts, toys et al; 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, disposable tableware et al.

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. Environmental benefits refer to the environmental impact of the output of various products in the recycling process(Kim et al., 2020). 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, the environmental impact of carbon dioxide and dioxins emitted by the recycling system, and estimates the carbon emission reductions of waste plastic recycling.

2.1.2 Construction of flow sheet and definition of parameters

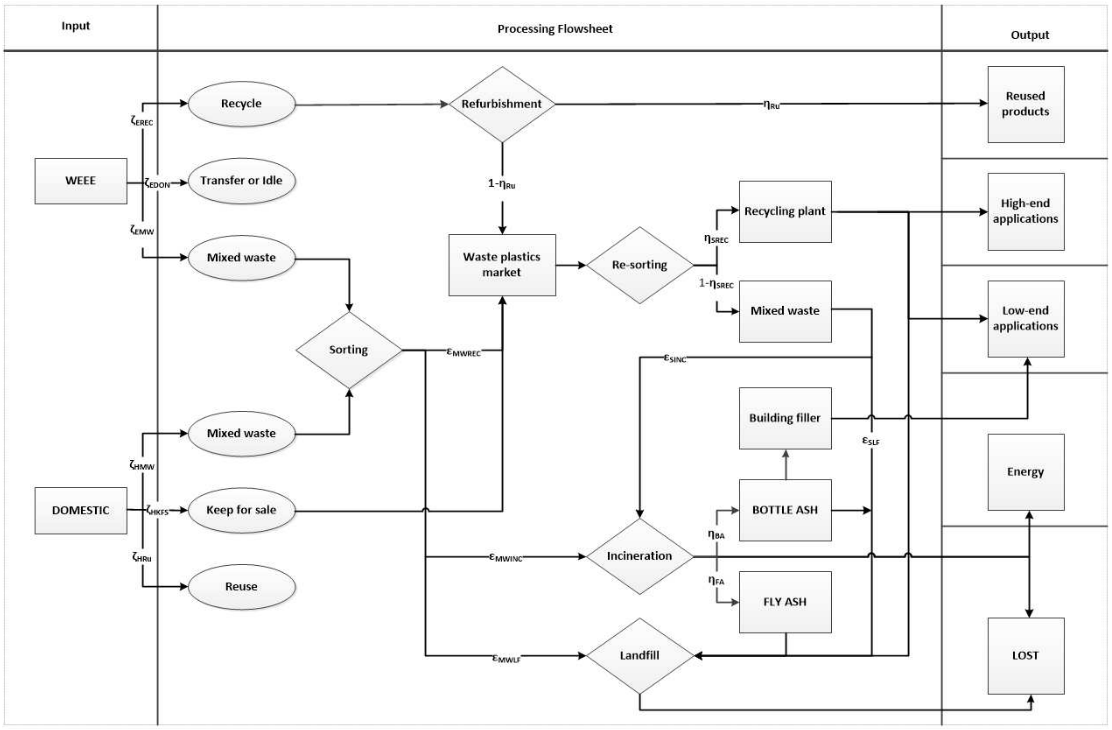

Fig. 1. Flow sheet of waste plastic flows from China's domestic households.

This paper mainly examines waste plastics from WEEE and domestic sources (Park et al.,2019). Fig.1 illustrates a flow sheet of waste plastic flows from domestics 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):

a) Direct recycling through formal channels;

b)Transfer to relatives or friends, or remain idle at home;

c) Direct discard into mixed waste.

In this case, ζ_{EREC} is the probability that residents recycle and reuse through formal channels, ζ_{EDON} is the probability that residents transfer WEEE to their relatives and friends for use or leave them as idle at home, and ζ_{EMW} is the probability that residents directly discard WEEE into mixed waste. Thus, the following formula can be attained: $\zeta_{EREC}+\zeta_{EDON}+\zeta_{EMW}=1$.

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, ζ_{HMW1} is the probability that residents discard waste plastics of high recycling value into mixed waste, ζ_{HKFS1} is the probability that residents choose to retain waste plastics with high recycling value for sale, and ζ_{HRu1} is the probability that residents choose to reuse waste plastics with high recycling value. Accordingly, ζ_{HMW2}, ζ_{HKFS2} and ζ_{HRu2} represent the probability that residents select the aforementioned three treatment methods for waste plastics with low recovery value. Thus, the relative formula is as follows: $\zeta_{HMW}+\zeta_{HKFS}+\zeta_{HRu}=1$.

WEEE, which is recycled through formal channels, normally entails manual sorting and repairing as the steps. η_{Ru} represents the efficiency of sorting refurbishment. As such, WEEE is refurbished and resold to consumers as second-hand products, typically with a relatively short product life cycle. After the failure of $1-\eta_{Ru}$ in WEEE refurbishment, relevant subsequent recycling is carried out, and the plastic component flows into the waste plastic market. Waste plastics in mixed waste is initially sorted by street recyclers and scavengers, as part of them can be extracted. Waste plastics of ε_{MWREC} in mixed waste is then sorted and recycled to the waste plastic market, while the remaining plastics (1-ε_{MWREC}) are either burned or landfilled with the mixed waste, the ratios of which are ε_{MWLF} and ε_{MWINC}, respectively. After these plastics flow into the waste plastic market, they are then re-sorted and divided as either renewable plastics for recycling or nonrenewable plastics. Re-sorting efficiency is denoted as η_{SREC}. Recyclable plastics can be processed for secondary use by crushing and recycling treatment(Tang, 2017). The remaining nonrenewable ones are used as mixed waste for subsequent incineration and landfill treatment (1-η_{SREC}). The ratio parameters for incineration and landfill are ε_{SINC} and ε_{SLF}, respectively.

There are two principal ways for treating mixed waste in China: incineration and landfill. Waste plastics tend to produce bottom ash and fly ash during incineration of mixed waste (He et al.,2005); respectively, the proportional parameters are η_{BA} and η_{FA}, while the remaining component (1-η_{BA}-η_{FA}) is lost as flue gas. Bottom ash can be utilized for building packing (Gu & Ozbakkaloglu,2016), a low-end application of waste plastics, while fly ash contains harmful substances that can cause considerable environmental damage. Therefore, ash treatment must be performed before landfilling (Bao,2012). Another disposal approach for mixed waste is by landfill, which is not only a waste of resources, but can also yield substantial pollution, especially when hazardous materials such as plastics are being landfilled.

The output of waste plastic recovery system has five components: second-hand products, high-end applications, low-end applications (Pooja et al, 2021), energy recovery (Chen,2018; Rajasekaran et al., 2018), and material loss.

a) Reused products: refurbished WEEE

b) High-end secondary materials: recycled plastic raw materials

c) Low-end secondary materials: building materials

d) Energy: energy recovery from incineration

e) Materials lost: materials lost upon incineration or landfill treatment

2.1.3 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).

$$\mathrm{TPR} = \mathrm{M_{Tweee}} * \zeta_{\mathrm{EREC}} * \eta_{\mathrm{Ru}} + \mathrm{M_{THWP}} * \zeta_{\mathrm{HRu}} \tag{1}$$

In the formula, $\mathrm{M_{Tweee}}$ stands for WEEE waste plastic production.

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

$$\mathrm{MTHEA} = [\mathrm{M_{Tweee}} * \zeta_{\mathrm{EREC}} * (1 - \eta_{\mathrm{Ru}}) + (\mathrm{M_{Tweee}} * \zeta_{\mathrm{EMW}} + \mathrm{M_{THWP}} * \zeta_{\mathrm{HMW}}) * \varepsilon_{\mathrm{MWREC}} + \mathrm{M_{THWP}} * \zeta_{\mathrm{HKFS}}] * \eta_{\mathrm{SREC}} * \eta_{\mathrm{REC}} \tag{2}$$

In the formula, $\mathrm{M_{THWP}}$ represents the output of waste plastics from domestic sources, η_{REC} represents the plastic recycling rate of waste plastic recycling plants

And material towards low-end applications (MTLEA):

$$\mathrm{MTLEA} = [\mathrm{M_{Tweee}} * \zeta_{\mathrm{EREC}} * (1 - \eta_{\mathrm{Ru}}) + (\mathrm{M_{Tweee}} * \zeta_{\mathrm{EMW}} + \mathrm{M_{THWP}} * \zeta_{\mathrm{HMW}}) * \varepsilon_{\mathrm{MWREC}} + \mathrm{M_{THWP}} * \zeta_{\mathrm{HKFS}}] * \eta_{\mathrm{SREC}} * (1 - \eta_{\mathrm{REC}}) * BM_{wp} + \{(\mathrm{M_{Tweee}} * \zeta_{\mathrm{EMW}} + \mathrm{M_{THWP}} * \zeta_{\mathrm{HMW}}) * \varepsilon_{\mathrm{MWINC}} + [\mathrm{M_{Tweee}} * \zeta_{\mathrm{EREC}} * (1 - \eta_{\mathrm{Ru}}) + (\mathrm{M_{Tweee}} * \zeta_{\mathrm{EMW}} + \mathrm{M_{THWP}} * \zeta_{\mathrm{HMW}}) * \varepsilon_{\mathrm{MWREC}} + \mathrm{M_{THWP}} * \zeta_{\mathrm{HKFS}}] * (1 - \eta_{\mathrm{SREC}}) * \varepsilon_{\mathrm{SINC}}\} * \eta_{\mathrm{BA}} * BM_{wp} \tag{3}$$

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.

$$\mathrm{TER} = \{(\mathrm{M_{Tweee}} * \zeta_{\mathrm{EMW}} + \mathrm{M_{THWP}} * \zeta_{\mathrm{HMW}}) * \varepsilon_{\mathrm{MWINC}} + [\mathrm{M_{Tweee}} * \zeta_{\mathrm{EREC}} * (1 - \eta_{\mathrm{Ru}}) + (\mathrm{M_{Tweee}} * \zeta_{\mathrm{EMW}} + \mathrm{M_{THWP}} * \zeta_{\mathrm{HMW}}) * \varepsilon_{\mathrm{MWREC}} + \mathrm{M_{THWP}} * \zeta_{\mathrm{HKFS}}] * (1 - \eta_{\mathrm{SREC}}) * \varepsilon_{\mathrm{SINC}}\} * \eta_{\mathrm{INC}} * CV_{wp} * TP_{wp} \tag{4}$$

In the formula, η_{INC} represents the Incineration efficiency of residential waste plastics, and CV_{wp} represents the calorific value of residential waste plastics, TP_{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.

$$\mathrm{MLI} = \{(\mathrm{M_{Tweee}} * \zeta_{\mathrm{EMW}} + \mathrm{M_{THWP}} * \zeta_{\mathrm{HMW}}) * \varepsilon_{\mathrm{MWINC}} + [\mathrm{M_{Tweee}} * \zeta_{\mathrm{EREC}} * (1 - \eta_{\mathrm{Ru}}) + (\mathrm{M_{Tweee}} * \zeta_{\mathrm{EMW}} + \mathrm{M_{THWP}} * \zeta_{\mathrm{HMW}}) * \varepsilon_{\mathrm{MWREC}} + \mathrm{M_{THWP}} * \zeta_{\mathrm{HKFS}}] * (1 - \eta_{\mathrm{SREC}}) * \varepsilon_{\mathrm{SINC}}\} * \eta_{\mathrm{INC}} * \left(1 - TP_{wp}\right) \tag{5}$$

$$\mathrm{MLLF} = (\mathrm{M_{Tweee}} * \zeta_{\mathrm{EMW}} + \mathrm{M_{THWP}} * \zeta_{\mathrm{HMW}}) * \varepsilon_{\mathrm{MWLF}} + [\mathrm{M_{Tweee}} * \zeta_{\mathrm{EREC}} * (1 - \eta_{\mathrm{Ru}}) + (\mathrm{M_{Tweee}} * \zeta_{\mathrm{EMW}} + \mathrm{M_{THWP}} * \zeta_{\mathrm{HMW}}) * \varepsilon_{\mathrm{MWREC}} + \mathrm{M_{THWP}} * \zeta_{\mathrm{HKFS}}] * (1 - \eta_{\mathrm{SREC}}) * \varepsilon_{SLF} + \{(\mathrm{M_{Tweee}} * \zeta_{\mathrm{EMW}} + \mathrm{M_{THWP}} * \zeta_{\mathrm{HMW}}) * \varepsilon_{\mathrm{MWINC}} + [\mathrm{M_{Tweee}} * \zeta_{\mathrm{EREC}} * (1 - \eta_{\mathrm{Ru}}) + (\mathrm{M_{Tweee}} * \zeta_{\mathrm{EMW}} + \mathrm{M_{THWP}} * \zeta_{\mathrm{HMW}}) * \varepsilon\varepsilon_{\mathrm{MWREC}} + \mathrm{M_{THWP}} * \zeta_{\mathrm{HKFS}}] * (1 - \eta_{\mathrm{SREC}}) * \varepsilon_{\mathrm{SINC}}\} * \eta_{\mathrm{FA}} + [\mathrm{M_{Tweee}} * \zeta_{\mathrm{EREC}} * (1 - \eta_{\mathrm{Ru}}) + (\mathrm{M_{Tweee}} * \zeta_{\mathrm{EMW}} + \mathrm{M_{THWP}} * \zeta_{\mathrm{HMW}}) * \varepsilon_{\mathrm{MWREC}} + \mathrm{M_{THWP}} * \zeta_{\mathrm{HKFS}}] * \eta_{\mathrm{SREC}} * (1 - \eta_{\mathrm{REC}}) * (1 - BM_{wp}) + \{(\mathrm{M_{Tweee}} * \zeta_{\mathrm{EMW}} + \mathrm{M_{THWP}} * \zeta_{\mathrm{HMW}}) * \varepsilon_{\mathrm{MWINC}} + [\mathrm{M_{Tweee}} * \zeta_{\mathrm{EREC}} * (1 - \eta_{\mathrm{Ru}}) + (\mathrm{M_{Tweee}} * \zeta_{\mathrm{EMW}} + \mathrm{M_{THWP}} * \zeta_{\mathrm{HMW}}) * \varepsilon_{\mathrm{MWREC}} + \mathrm{M_{THWP}} * \zeta_{\mathrm{HKFS}}] * (1 - \eta_{\mathrm{SREC}}) * \varepsilon_{\mathrm{SINC}}\} * \eta_{\mathrm{BA}} * (1 - BM_{wp}) \tag{6}$$

In the above formula, BM_{wp} represents the utilization rate of waste residue as a building material.

$$TML= MLI+ MLLF \quad (7)$$

The calculation of these formulae is necessary for an MFA procedure. It is vital to clearly delineate the significant parameters in the entire material flow process. Through changing the values of relevant parameters, one can observe the changes in the overall material system. In this way, one can determine the key portion of the process and provide decision-based support for future system improvement.

2.1.4 Linking MFA to LCA

Inventory analysis is a qualitative and quantitative analysis of resource and energy use and the waste discharged into the environment (e.g., air, water and soil) in the whole life cycle of the system under study, such as the processes and activities of products(Zinia and McShane, 2021).In the residential waste plastic recycling system, this study determines the input (raw materials, auxiliary materials and energy, etc.) and output (discharge to air, water, soil and solid waste) at each stage of the life cycle to form a complete life cycle inventory(Huo, 2003). Then, the life cycle impact assessment (LCIA) is used to qualitatively and quantitatively evaluate the environmental impact identified by the inventory analysis to determine the impact of the material and energy exchange of the recycling system on the external environment(Ren and Liu, 2002).

Under normal circumstances, the carbon dioxide emissions from plastic incineration account for an absolute proportion(Zhong et al., 2019). However, as the amount of waste plastics produced continues to increase, both energy consumption and plastic incineration volume in the recycling phase will gradually increase, and carbon emissions 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 (10)(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 (11).

$$CE = [\mathrm{M_{Tweee}} * \zeta_{\mathrm{EREC}} * (1-\eta_{\mathrm{Ru}}) + (\mathrm{M_{Tweee}} * \zeta_{\mathrm{EMW}} + \mathrm{M_{THWP}} * \zeta_{\mathrm{HMW}}) * \varepsilon_{\mathrm{MWREC}} + \mathrm{M_{THWP}} * \zeta_{\mathrm{HKFS}}] * \eta_{\mathrm{SREC}} * \eta_{\mathrm{REC}} * EF_{wpr} + \{(\mathrm{M_{Tweee}} * \zeta_{\mathrm{EMW}} + \mathrm{M_{THWP}} * \zeta_{\mathrm{HMW}}) * \varepsilon_{\mathrm{MWINC}} + [\mathrm{M_{Tweee}} * \zeta_{\mathrm{EREC}} * (1-\eta_{\mathrm{Ru}}) + (\mathrm{M_{Tweee}} * \zeta_{\mathrm{EMW}} + \mathrm{M_{THWP}} * \zeta_{\mathrm{HMW}}) * \varepsilon_{\mathrm{MWREC}} + \mathrm{M_{THWP}} * \zeta_{\mathrm{HKFS}}] * (1-\eta_{\mathrm{SREC}}) * \varepsilon_{\mathrm{SINC}}\} * \eta_{\mathrm{INC}} * EF_{wpi}$$

(8)

$$CR = [\mathrm{M_{Tweee}} * \zeta_{\mathrm{EREC}} * (1-\eta_{\mathrm{Ru}}) + (\mathrm{M_{Tweee}} * \zeta_{\mathrm{EMW}} + \mathrm{M_{THWP}} * \zeta_{\mathrm{HMW}}) * \varepsilon_{\mathrm{MWREC}} + \mathrm{M_{THWP}} * \zeta_{\mathrm{HKFS}}] * \eta_{\mathrm{SREC}} * \eta_{\mathrm{REC}} * (EF_{pp} - EF_{wpr}) \qquad (9)$$

Dioxin compounds can cause greater harm to human health and have a persistent presence in the environment (Wang et al., 2020). The dioxins produced by the incineration of waste plastic is mainly discharged into fly ash and the atmosphere, and the dioxin discharged into the fly ash flows to landfill after being harmless and stabilized (Zhan et al., 2016). In this study, the emission factor estimation method was used to estimate the dioxin emission from waste plastic incineration (Liang et al., 2011).

$$DE = \{(\mathrm{M_{Tweee}} * \zeta_{\mathrm{EMW}} + \mathrm{M_{THWP}} * \zeta_{\mathrm{HMW}}) * \varepsilon_{\mathrm{MWINC}} + [\mathrm{M_{Tweee}} * \zeta_{\mathrm{EREC}} * (1-\eta_{\mathrm{Ru}}) + (\mathrm{M_{Tweee}} * \zeta_{\mathrm{EMW}} + \mathrm{M_{THWP}} * \zeta_{\mathrm{HMW}}) * \varepsilon_{\mathrm{MWREC}} + \mathrm{M_{THWP}} * \zeta_{\mathrm{HKFS}}] * (1-\eta_{\mathrm{SREC}}) * \varepsilon_{\mathrm{SINC}}\} * EF_d \qquad (10)$$

In the above formula, DE stands for the amount of dioxins emitted from the incineration of waste plastics to the atmosphere, in g TEQ; EF_d is the emission factor of dioxins produced by the incineration of waste plastics, which is 30μg TEQ/t(Sun et al., 2016;United Nations Environment Programme Division, 2005).

2.2. Description of case study and data inventory

The combination of MFA and LCA can improve the economic and environmental performance of the recycling chain. However, such method is usually suitable for the evaluation of past fait accompli – that is, data availability(De Meester et al., 2019). This paper intends to take the production and recycling of waste plastics in China in 2019 as the representative case, utilizing the combination of MFA and LCA for quantitative analysis.

2.2.1 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.

Table 1 Scale of waste plastics production by various industries in China in 2019.

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)
Household	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)

2.2.2 Data inventory

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 discarded them into mixed waste(China Electronics Chamber Of Commerce, 2016; Li et al., 2021). Regarding waste plastics generated from households, 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(Association, 2019). 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).

Table 2 Recycling process-related parameters

	Parameters	Numerical value	Data source
WEEE to Recycle	ζ_{EREC}	52.09%	(Li et al., 2021)
WEEE to Transfer or idle	ζ_{EDON}	44.21%	(Li et al., 2021)
WEEE to Discard to mixed waste	ζ_{EMW}	3.70%	(China Electronics Chamber Of Commerce, 2016)
High recovery value waste plastic to Discard to mixed waste	ζ_{HMW1}	27.0%	(Thanh et al., 2011)
High recovery value waste plastic to keep for sale	ζ_{HKFS1}	69.0%	(Thanh et al., 2011)
High recovery value waste plastic to reuse	ζ_{HRu1}	4.0%	(Thanh et al., 2011)
Low recovery value waste plastic to Discard to mixed waste	ζ_{HMW2}	64.0%	(Thanh et al., 2011)
Low recovery value waste plastic to keep for sale	ζ_{HKFS2}	28.0%	(Thanh et al., 2011)
Low recovery value waste plastic to reuse	ζ_{HRu2}	8.0%	(Thanh et al., 2011)
Mixed waste to classification recovery	$\varepsilon_{\mathrm{MWREC}}$	3.7%	(Editorial Board Of Statistics, 2020)
Mixed waste to landfill	$\varepsilon_{\mathrm{MWLF}}$	45.6%	(Editorial Board Of Statistics, 2020)
Mixed waste to incineration	$\varepsilon_{\mathrm{MWINC}}$	50.7%	(Editorial Board Of Statistics, 2020)
Classification refurbishment rate	η_{Ru}	50%	(De Meester et al., 2019)
Sorting to waste plastic plant	η_{SREC}	63%	(Recycling Plastics Branch of Association, 2019)
Mixed waste in waste plastic plant to landfill	$\varepsilon_{\mathrm{SLF}}$	60%	(Recycling Plastics Branch of Association, 2019)
Mixed waste in waste plastic plant to incineration	$\varepsilon_{\mathrm{SINC}}$	40%	(Recycling Plastics Branch of Association, 2019)
Incineration to bottle ash	η_{BA}	22%	(Yao, 2014)
Incineration to fly ash	η_{FA}	3%	(Yao, 2014)
Recycling efficiency of waste plastics	η_{REC}	82%	(De Meester et al., 2019)
Incineration efficiency	η_{INC}	75%	(Yao, 2014)
Utilization rate of waste residue as building materials	BM_{wp}	98%	(Baidu library, 2016)
Calorific value of waste plastic	CV_{wp}	44MJ/kg	(De Meester et al., 2019)
Energy recovery rate of waste plastic incineration	TP_{wp}	25.6%	(Liu et al., 2014)

Carbon emissions from waste plastic incineration	EF_{wpi}	2.75t CO^{2} eq/t	(IPCC, 2006; Quick And Easy Financial Network, 2021)
Carbon emissions from waste plastic recycling	EF_{wpr}	1.57 t CO^{2} eq/t	(Dai et al., 2021)
Carbon emissions from the original production of plastics	EF_{pp}	4.487t CO^{2} eq/t	(Easy Carbon Home, 2019)
Dioxin emitted into the atmosphere by incineration of waste plastics	EF_{d}	30μg TEQ/t	(United Nations Environment Programme Division, 2005)

3. Results analysis

3.1. Base year analysis

The recycling situation for waste plastics by Chinese residents in 2019 is presented in Table 3, and using e-sankey 4.0 software, the material flow chart for the recycling of waste plastics by Chinese residents in 2019 was drawn. Fig.2 shows the material flow at each stage of the recovery cycle for residents' waste plastics in 2019. Overall, 8.39 million tons of high-end applications were recovered, with a recovery rate of approximately 25.9%, and 3.68 million tons of low-end applications were recovered. The energy recovery is 8.9*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.

Table 3 The recycling situation of waste plastics in China in 2019

Output index	Unit	Recovery amount
Total Product Recovery (**TPR**)	kt	1148.6
High end application (**MTHEA**)	kt	8390
Low end application (**MTLEA**)	kt	4076.6
Energy recovery (**TER**)	MJ	8.90*10^10
Lost (**TML**)	kt	17199.6
Reuse of waste plastics from domestic sources	kt	2067.4
Transfer or idle of waste plastics from WEEE sources	kt	1949.7
Carbon emissions (**CE**)	kt	34904.8
Carbon reduction (**CR**)	kt	24473.6

Dioxin emissions (**DE**)	g TEQ	316.11

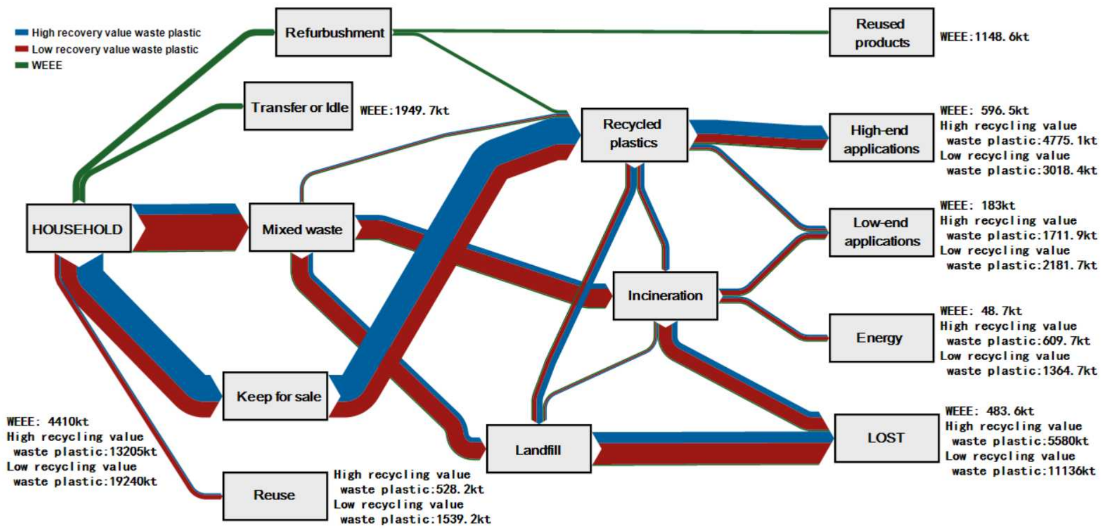

Fig. 2. Flows of different waste plastics towards various valorization pathways.

3.2. 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 as influenced by the changes of these factors through changing the values of the relevant variables one-by-one(Christopher and R, 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, as confirmed in various literatures (Knickmeyer, 2020; Hui et al., 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. The appendix A 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: ζ_{EREC}, ζ_{HKFS1}, ζ_{HKFS2}

Technological progress: η_{Ru}, η_{SREC}, η_{INC}, η_{REC}, TP_{wp}

Government policy: $\varepsilon_{\mathrm{MWREC}}$, $\varepsilon_{\mathrm{MWINC}}$, $\varepsilon_{\mathrm{SINC}}$

3.2.1 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; Yeow, 2018). 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 (ζ_{EREC}), the TPR recycling rate increases by 1.9%; for every 5% increase in the recycling selection rate of high-value waste plastics (ζ_{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 (ζ_{HKFS2}), the recovery rate 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.

3.2.2 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 η_{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 η_{REC}, the MTHEA recovery rate and CR both increase by 1.2%. Obviously, the classification refurbishment rate (η_{Ru}), waste plastic recycling efficiency (η_{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 (η_{SREC}) has a significant impact on the amount of recycled plastics recycled and carbon reductions for every 5% increase in η_{SREC}, the MTHEA recovery rate and CR both increase by 7.9%. Increasing incineration efficiency (η_{INC}) can not only increase energy production for every 5% increase in η_{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 η_{SREC} and η_{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.

3.2.3 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(Ming 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 $\boldsymbol{\varepsilon}_{\mathbf{MWREC}}$ increases by 5% and $\boldsymbol{\varepsilon}_{\mathbf{MWLF}}$ decreases by 5%, the MTHEA recovery rate and CR both increase by 4.9%; When $\boldsymbol{\varepsilon}_{\mathbf{MWREC}}$ increases by 5% and $\boldsymbol{\varepsilon}_{\mathbf{MWINC}}$ decreases by 5%, MTHEA recovery rate and CR both increase by 3.8%, 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 $\boldsymbol{\varepsilon}_{\mathbf{SINC}}$ increases by 5% and $\boldsymbol{\varepsilon}_{\mathbf{SLF}}$ decreases by 5%, TEP recovery rate increase by 2.9%; When $\boldsymbol{\varepsilon}_{\mathbf{MWINC}}$ increases by 5% and $\boldsymbol{\varepsilon}_{\mathbf{MWLF}}$ decreases by 5%, TEP recovery rate increase 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 is 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.

3.3. Scenario prediction

3.3.1 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 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.

$$M_{tWPi}= M_{WP}*(1+r)^{t}*\boldsymbol{\varepsilon_i} \tag{11}$$

M_{tWPi} 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 $\boldsymbol{\varepsilon_i}$ 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.

Table 4 Prediction of production of waste plastics (10,000 tons)

Year	2019	2020	2021	2022	2023	2024	2025	2030	2035
WEEE source	441.0	452.0	463.3	474.9	486.8	499.0	511.4	578.6	654.7
Domestic source	3244.5	3325.6	3408.8	3494.0	3581.3	3670.9	3762.6	4257.1	4816.5
High recycling value	1320.5	1353.5	1387.4	1422.0	1457.6	1494.0	1531.4	1732.6	1960.3
Low recycling value	1924.0	1972.1	2021.4	2071.9	2123.7	2176.8	2231.3	2524.5	2856.2

3.3.2 Scenario prediction of residents' waste plastic recycling in China in the future

Considering the quantity and composition of plastic solid waste, Thanh et al. (2011) put forward an optimization of a disposal scheme for waste plastics with regard to a certain time sequence level. The relatively large proportion of waste plastics from domestic source and WEEE in China are the essential factors for consideration in the scenario setting in this paper. Waste plastics from domestic source are further classified into two categories: high recovery value and low recycling value. In this case, the quantity and value of waste plastics are being comprehensively considered. Additionally, scenario setting is usually combined with the LCA method. Rigamonti et al. (2014) utilized the LCA to comprehensively consider the recycling means, separation methods and separation efficiency of waste plastics, established an EASEWASTE model, defined five plastic waste scenarios, and examined the material and energy recovery of waste plastics. Gradus et al., (2017) investigated the conventional incineration treatment and energy recovery of domestic waste plastics in the Netherlands; the environmental benefits of both scenarios were computed according to the avoided carbon dioxide emissions, after which a related cost-benefit analysis was conducted. 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 paper, the most 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. Future benefits are predicted up to the year 2035.

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). Hence, this paper comprehensively considers the specific implementation of policies in China and the respective situations of developed countries, and generates a scientific forecast for China's plastic recovery schemes.

Scenario 3: Alongside the development of science and technology, the re-sorting rate of waste plastics recycling plants has gradually increased. The separation technologies for waste plastics recovery can be categorized as either density separation, dissolution separation, filtration separation, electrostatic separation or floating separation(Xiong, 2014). 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 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. Meanwhile, this paper comprehensively considers the application of artificial sorting, mechanization sorting and other innovative sortation technologies in waste plastic recycling plants according to China's development of its waste plastic recycling systems, thus rendering a scientific prediction of the future re-selecting efficiency and the relative improvement in recovery.

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.

There are various requirements laid out in the Industrial Green Development Plan (2016 / 2020). By 2020, the recycling volume of waste plastics in China must reach 23 million tons. It is crucial to accelerate the efficient utilization of renewable resources and the standardized development among industries, as well as the popularization and application of the advanced and applicable recycling technology and equipment concerning major renewable resources, such as waste plastics. This further calls for establishing industrial agglomeration areas for renewable resources, promoting a cross-regional cooperative utilization of renewable resources, generating a system for recycling and utilization of regional renewable resources, and endorsing the industries' gradual standardization. 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. By referring to developed states that have highly efficient recycling systems for waste plastics, the key links in the future recycling systems for China's waste plastics can be predicted. The parameters are primarily based on the existing economic and technological development levels in China, and the implementation of policies and development status of developed nations, through encompassing the three levels involving residents, technology and the government. Therefore, the scenario prediction model set up in this study is shown in Table 5.

Table 5 Scenario setting

Year	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2035
Scenario 1: Consumer behavior													
ζ_{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
ζ_{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
ζ_{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													
ε_{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
ε_{SINC}	0.4	1	1	1	1	1	1	1	1	1	1	1	1
Scenario 3: Technological progress													
η_{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)													

The predicted values for each key parameter are inputted into the mathematical model, after which the benefit values for each scenario can be estimated. It can be seen from Table 6 that the amount of recycled plastic waste and environmental benefits of residents have been continuously improved. Under the development of Scenario 4, 33960.3 kilotons of high-end application materials will be recycled by 2035, with a recovery rate of approximately 62%, and emission of 64729 kilotons of carbon dioxide, with a total carbon reduction of 99062.3 kilotons relative to the original production. Recycling can bring huge environmental benefits. It can be seen from Figure 3 that as the amount of waste increases, the effect of reducing carbon dioxide and dioxins is very significant. Moreover, as can be seen from Figure 3, under Scenario 4, carbon emissions gradually tend to stabilize, which is in line with China’s goal of achieving a carbon peak by 2035. Whether accomplished by improving the residents’ willingness to recycle, standardizing waste separation and recycling, or enhancing re-sorting efficiency, it is vital to improve the recycling efficiency of China’s waste plastic system.

Table 6 Scenario prediction of residents' waste plastic recycling

		Unit	2020	2021	2022	2023	2024	2025	2030	2035
	Total Product Recovery (**TPR**)	kt	1188.6	1229.9	1272.5	1316.5	1361.9	1398.5	1591.2	1800.3
Scenario 1	High end application (**MTHEA**)	kt	9230.4	10107.5	11022.7	11977.4	12973.0	13929.7	18079.3	21937.3
	Low end application (**MTLEA**)	kt	4213.3	4354.3	4499.7	4649.6	4804.2	4960.2	5743.6	6583.1

	Energy recovery (**TER**)	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	7.27*10^10	7.30*10^10
	Lost (**TML**)	kt	17042.8	16867.3	16672.5	16457.3	16221.0	16044.9	16020.8	16767.6
	Carbon emissions (**CE**)	kt	35802.4	36722.9	37667.2	38635.7	39629.0	40654.2	46123.5	52271.9
	Carbon reduction (**CR**)	kt	26925.0	29483.6	32153.4	34938.2	37842.1	40632.9	52737.2	63991.0
	Dioxin emissions (**DE**)	g TEQ	309.97	303.33	296.17	288.45	280.17	273.23	258.02	259.35
	Total Product Recovery (**TPR**)	kt	1177.3	1206.7	1236.9	1267.8	1299.5	1332.0	1507.0	1705.1
	High end application (**MTHEA**)	kt	9873.9	11426.8	13051.2	14749.6	15774.7	16418.9	19228.9	21841.9
	Low end application (**MTLEA**)	kt	5268.9	5701.6	6152.6	6622.6	6952.4	7138.4	8045.2	9098.3
Scenario 2	Energy recovery (**TER**)	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
	Lost (**TML**)	kt	14538.1	13276.8	11943.3	10534.9	9957.1	9981.1	10824.2	12184.7
	Carbon emissions (**CE**)	kt	45586.6	48967.9	52489.8	56157.2	58812.5	60276.8	67581.0	76380.3
	Carbon reduction (**CR**)	kt	28802.2	33332.0	38070.3	43024.6	46014.8	47894.0	56090.8	63712.8
	Dioxin emissions (**DE**)	g TEQ	437.59	451.31	465.45	480.01	495.22	501.81	543.88	612.20
	Total Product Recovery (**TPR**)	kt	1177.3	1206.7	1236.9	1267.8	1299.5	1332.0	1507.0	1705.1
	High end application (**MTHEA**)	kt	9145.8	9934.1	10756.1	11319.0	11903.3	12509.8	15027.3	17792.8
	Low end application (**MTLEA**)	kt	4238.6	4406.1	4579.3	4726.1	4877.4	5033.3	5790.8	6638.7
Scenario 3	Energy recovery (**TER**)	MJ	8.90*10^10	8.89*10^10	8.88*10^10	8.98*10^10	9.08*10^10	9.18*10^10	1.00*10^11	1.10*10^11
	Lost (**TML**)	kt	17074.7	16932.8	16773.1	16893.6	17009.7	17121.0	18483.0	20108.1
	Carbon emissions (**CE**)	kt	36085.4	37303.1	38559.2	39688.9	40851.1	42046.5	48064.5	54826.5
	Carbon reduction (**CR**)	kt	26678.2	28977.7	31375.5	33017.5	34721.9	36491.0	43834.7	51901.7
	Dioxin emissions (**DE**)	g TEQ	316.02	315.73	315.23	318.81	322.37	325.91	355.95	391.15
	Total Product Recovery (**TPR**)	kt	1188.6	1229.9	1272.5	1316.5	1361.9	1398.5	1591.2	1800.3
	High end application (**MTHEA**)	kt	11066.1	13876.7	16787.4	19259.6	21080.7	22575.3	28277.2	33960.3
	Low end application (**MTLEA**)	kt	5307.7	5724.2	6101.9	6463.0	6694.5	6829.7	7594.5	8498.5
Scenario 4	Energy recovery (**TER**)	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
	Lost (**TML**)	kt	13489.8	11230.3	8983.0	7141.8	6092.8	5521.1	4277.2	3426.7
	Carbon emissions (**CE**)	kt	45375.8	47989.2	50182.2	52430.3	53755.7	54320.5	58854.6	64729.0
	Carbon reduction (**CR**)	kt	32279.7	40478.3	48968.8	56180.4	61492.5	65852.1	82484.6	99062.3
	Dioxin emissions (**DE**)	g TEQ	407.30	381.13	346.56	322.80	300.49	274.58	210.32	165.98

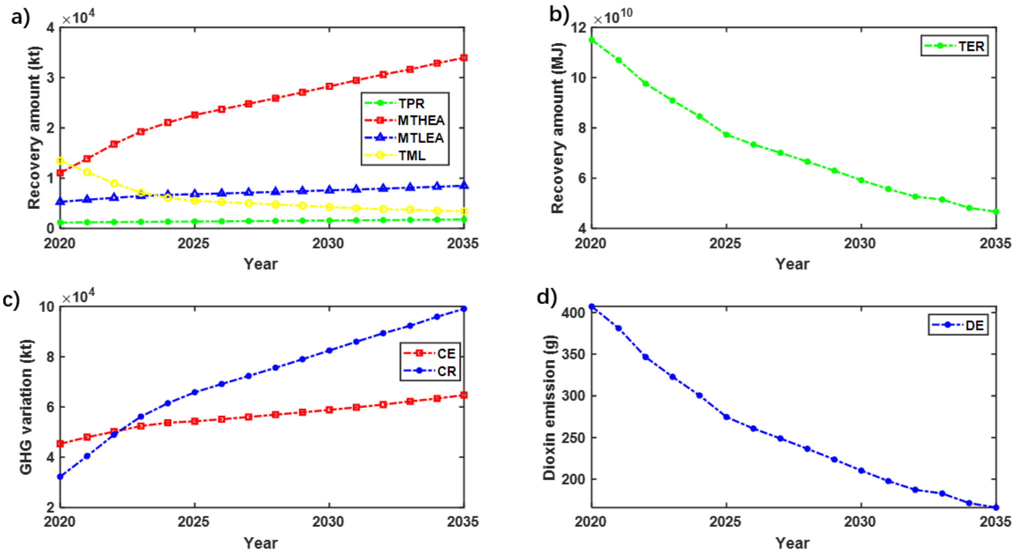

Fig. 3. Prediction of residents' waste plastics recycling in China from 2020 to 2035

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 Figure 4.

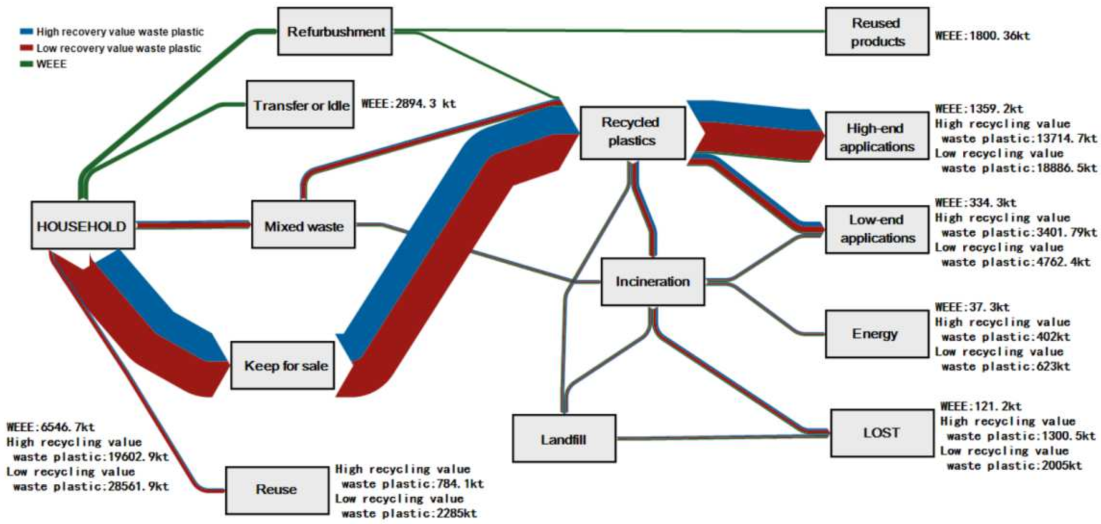

Fig.4. Material flow of Chinese residents' waste plastic recycling system in 2035

4. 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. 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 several materials. 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 concerns 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 is 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. 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.

5. 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 paper 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 plastics or the energy recovery by incineration, in order to mitigate the proportion of direct abandonment or landfill, especially for plastics with low recycling values. 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.

Author contribution Manzhi Liu: Conceptualization, Funding acquisition, Supervision, Project administration, Methodology, Investigation, Formal analysis, Writing original draft. Jixin Wen: Investigation, Writing original draft , Formal analysis, Data curation, Software. Linlin Zhang: Project administration, Data curation, Writing original draft, Formal analysis. Jixin Wu: Project administration, Formal analysis, Software. Xiaotao Yang: Investigation, Data curation. Ying Qin: Investigation, Data curation. Yingjie Liu: Investigation, Data curation.

Funding This research is financially supported by The National Natural Science Foundation of China (No. 71874186), The Key Project of Philosophy and Social Science Research in Colleges and Universities in Jiangsu Province (No. 2018SJZDI084), Jiangsu Social Science Fund Base Project (No.19JD010), National Key R&D Program of China(No. SQ2019YFC190057).

Data availability All data generated or analyzed during this study are included in this published article and the supporting information fles.

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.

Consent to participate Not applicable in this section.

Consent for publication Not applicable in this section.

Competing interests The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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