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GHG emissions reduction patterns from waste sectors after forced source separation

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ABSTRACT

Waste management is the bridge to balance resource conservation and climate change protection, and source separation is the pre-requirement to improve the recycling rate and normal human behavior. In this work, greenhouse gas (GHG) emission patterns were investigated from waste sectors from 2016 to 2021 in Shanghai, where force MSW source separation was first implemented in China since 2019. The GHG emission in the waste sector increased from 3.06 (2016) to 9.28 (2021) Mt CO_2-eq due to the increase of waste disposal amounts from 7.35 (2016) to 11.83 Mt (2021). With the implementation of forced source separation in Shanghai on July 1st, 2019, the proportion of kitchen waste and water content decreased by 37.31% and 20.74% in dry waste, resulting in the increase of low heating value (LHV) by 99.39% (13,160 kJ/kg). The waste disposal system was optimized by employing resource recycling and anaerobic digestion of wet waste, and the corresponding GHG emission intensity decreased from 0.29 to 0.24 t CO_2-eq per ton MSW. Three scenario analyses, including the Business-As-Usual (BAU) scenario, New Policy (NP) scenario, and Low-carbon (LC) scenario, were conducted to study the influence of the grid emission factor, wet waste disposal capacity, incineration power generation efficiency, and lower waste plastic proportion on the GHG emissions. The results showed that the GHG emission intensity would reach 0.28, 0.21, and 0.12 t CO_2-eq per ton MSW in the BAU, NP, and LC scenarios. Optimizing waste disposal mode and reducing waste plastic from sourced separation was critical to reduce GHG emissions more effectively from the waste sector.

1. Introduction

With the development of urbanization and the economy, the amount of municipal solid waste (MSW) has been increasing. China has become the largest MSW producer in the world, producing around 248.69 Mt in 2021. And since the 1980 s, the MSW disposal amount in China has grown at an average annual rate of 5.4% (Song et al., 2016; Wang and Geng, 2015). In order to dispose of MSW reasonably and effectively and reduce secondary pollution, China has proposed the waste disposal principles of reduction, recycling, and harmless and has been gradually changing the way of waste disposal from landfill to incineration for power generation (Chi et al., 2014; Li et al., 2015). Nowadays, the MSW harmless disposal rate has reached 99.88% (2021) in China, but China is still facing colossal waste disposal pressure due to the continuous increase in the production of MSW. Therefore, taking adequate measures to reduce the source volume of MSW and improve resource recycling efficiency has become the focus in the waste sector.

Promoting forced source separation is an essential method of reducing, reusing, and recycling MSW, and at present, many countries

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Nomenclature

Abbreviation	Definition
BAU	Business-As-Usual
BP neural network	Back Propagation neural network
CDM	Clean Development Mechanism
CH_4	methane
CO_2	carbon dioxide
CO_2-eq	CO_2 equivalent
FOD	First-Order Decay
GHG	greenhouse gas
GWP	global warming potential
IPCC	Intergovernmental Panel on Climate Change
IPCC AR5	Intergovernmental Panel on Climate Change Fifth Assessment Report
kg	kilogram
kJ	kilojoule
LC	Low-carbon
MSW	municipal solid waste
Mt	million ton
MWh	milliwatt-hour
N_2O	nitrous oxide
NP	New Policy
t	ton

have implemented forced source separation policies, such as Japan, the United States, and the European Union (Rathore and Sarmah, 2019; Wei and Lu, 2019; Wen et al., 2014; Yuan et al., 2020; Zhang et al., 2015; Zhang and Wen, 2014). The primary MSW disposal mode forced on the mixed waste landfilled and incineration, with higher kitchen waste content, higher water content, and lower heating value (LHV) in most cities of China (Chen et al., 2020; Yang et al., 2013; Zhang et al., 2010). In 2017, the Chinese government published *an Implementation plan for a domestic waste classification system* to put the source separation officially. Many previous studies have shown that GHG emissions from MSW could be significantly reduced after forced source separation, as it could separate organic matter and recyclable materials from mixed MSW and reduce the amount of waste disposal (Dong et al., 2013; Li et al., 2022; Liu et al., 2021; Tai et al., 2011; Xiao et al., 2021; Yao et al., 2019; Zhang et al., 2022). Du et al. (2022) showed that with the increase in wet waste separation proportion, the total and net GHG emissions gradually decreased. Bian et al. (2022) investigated the GHG emission in Qingdao under different waste disposal modes, and the results showed that implementing forced source separation could contribute to the minor GHG emission. In this paper, the data were respectively collected from the cases with long-term MSW separation, and the impact of waste recycling and wet waste treatment on GHG emissions was considered in the practical project, which could provide the authentic and convincing data and experience for the assessment of the GHG emissions from the waste sector.

Shanghai, the first city in China to enforce a forced source separation policy, was selected as the case city to reflect the more actual and reliable data in the waste sectors, and also, its waste disposal mode shifted from mixed waste disposal to classified disposal (Chen et al., 2020). In this work, the bottom-up method and the First-Order-Decay (FOD) method recommended by IPCC were combined to calculate the GHG emissions of MSW disposal in Shanghai from 2016 to 2021, and the changes in GHG emissions before and after forced source separation were analyzed. In addition, the scenario analysis was employed to predict GHG emissions from the waste sector in Shanghai until 2030, and the MSW generation amount was simulated by the Back Propagation (BP) neural network model, where MSW components, power generation efficiency, and wet waste disposal capacity were considered as the variables. This work will provide scientific support for implementing Shanghai's carbon peaking and carbon neutrality strategies in the waste sector.

2. Materials and methods

2.1. MSW disposal mode in Shanghai

Shanghai, the largest city in China, has 31 harmless disposal facilities for MSW in 2021, including 14 incineration facilities, 10 wet waste disposal facilities, and 7 landfills. The total MSW disposal capacity has reached 29,380 t/d, among which the incineration disposal capacity has reached 23,000 t/d. The wet waste disposal capacity has reached 6380 t/d, and the harmless disposal rate of MSW has reached 100%. With the development of the economy and society, the population increased from 24.67 million to 24.89 million, and the amount of MSW generated in Shanghai had been increasing, from 7.35 Mt (2016) to 12.29 Mt (2019), but with the implementation of forced source separation and the influence of Covid-19, it dropped to 10.76 Mt (2020) and rose back to 11.94 Mt in 2021. Per capita MSW generation increased from 291 kg (2016) to 374 kg (2021), reaching a peak of 436 kg in 2019. The MSW treatment system in Shanghai was mainly based on landfill, incineration, and composting, and with the implementation of forced source separation, the primary MSW disposal method in Shanghai changed from landfill to incineration. As shown in Fig. 1(a), due to its mature technology and low cost, the landfill was the primary MSW disposal method, accounting for 40.57–44.79% before 2019, but it dropped to 6.81% in 2021. Meanwhile, the proportion of incineration disposal exceeded that of the landfill in 2019 and reached 56.22% in 2021. Moreover, the amount of MSW recycling had risen sharply to 2.63 Mt, which accounted for 22.23%. The waste disposal capacity of each district in Shanghai is shown in Fig. S1 of SI.

Implementing forced source separation has changed the MSW component entering the terminal disposal facility. As shown in Fig. 1(b), before the forced source separation, the incoming waste at the terminal disposal facilities in Shanghai was mixed waste, mainly composed of kitchen waste, paper, and plastics, so the organic matter and water content were very high. While after forced source separation, MSW was divided into dry and wet waste, and rubber and plastics replaced kitchen waste as the main dry waste component, accounting for 41.57%. The proportion in dry waste of organic matter content (including kitchen waste, paper, textile and wood, and bamboo) dropped from 77.08% (2016) to 47.53% (2021), and the purity of wet waste reached 99.58%. The characteristics of MSW have also changed. The water content of dry waste decreased from 56.96% to 36.22%, and the low heating value (LHV) increased from 6600 kJ/kg to 12,580 kJ/kg and 13,525 kJ/kg.

2.2. The assessment of GHG emissions

The assessment of GHG emissions was based on the annual disposal volume of MSW disposal facilities in Shanghai, and specific emission factors were formulated for each disposal facility through field investigation, literature review, and expert judgment, while the bottom-up method was used to calculate the GHG emissions of different waste disposal facilities. CO_2 equivalent (CO_2-eq) was used as a measuring unit of GHG emissions. According to IPCC (2006) guidelines, the total GHG emissions from the waste sector include the GHG emissions from landfill, incineration, and biological disposal (IPCC, 2006).

CH_4 is the main GHG emitted from landfill, and its proportion typically reaches 45%– 60% (Rafiq et al., 2018). The FOD model is used to calculate the GHG emissions from landfill disposal. According to previous research, this study formulated specific emission factors based on

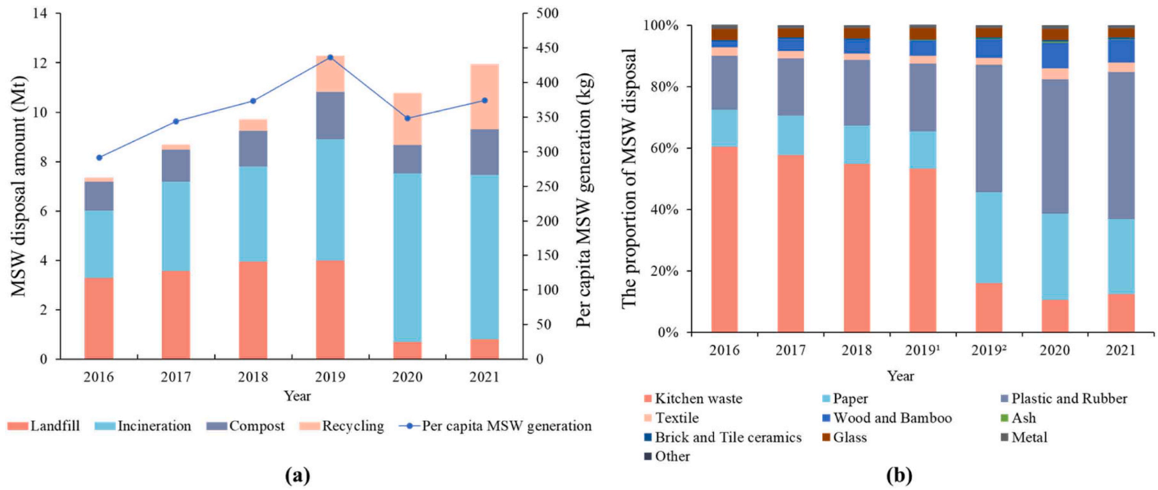

Fig. 1. (a): The population and MSW disposal amount in Shanghai (2016–2021); (b): The proportion of MSW disposal in Shanghai (2016–2021).
Note: In Fig. 1(a), the left axis used by the bar chart represents the MSW disposal amount, and the right axis used by the line chart represents the per capita MSW production. In Fig. 1(b), 2019[1] represents the first half of 2019, and 2019[2] represents the second half of 2019.

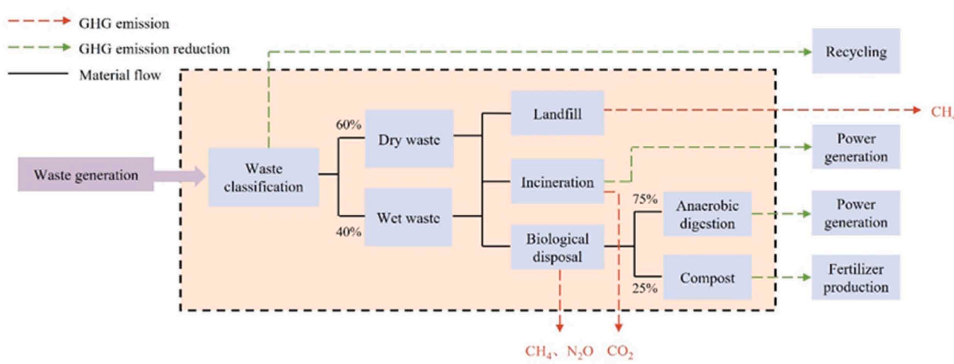

Fig. 2. The system boundary and carbon emission inventories.

the situation of each landfill. The formula is as follows (Eq.(1)) (IPCC, 2006):

$$E_{Lan-ch_4} = MSW_{Lan} \cdot \sum_{i=1}^{4} MCF \cdot f_i \cdot DOC_i \cdot DOC_F \left(e^{-(T-1)\cdot k_i} - e^{-T\cdot k_i}\right) \cdot F \cdot 16 / 12 \cdot (1-R)(1-OX) \quad (1)$$

Where E_{Lan-CH_4} is the CH_4 emitted in the year T during the operation. MSW_{Lan} is the mass of MSW amount landfilled when the landfill started operation. MCF is the CH_4 correction factor. F_i is the proportion of different MSW components. i is the MSW component. DOC_i is the proportion of degradable organic carbon in the waste component i. DOC_F is the proportion of DOC decomposing under anaerobic conditions. T is the length of time that the landfill has been operating. k_i is the rate of reaction constant. F is the volume fraction of CH_4 in the generated landfill gas. R is the CH_4 recovery rate, and OX is the oxidation factor. The values of CH_4 emission factors from landfills in Shanghai are shown in Table S3, S4, S5, and S6 of SI.

In the waste incineration process, the fossil carbon in the waste (such as plastic, textile, and rubber) is oxidized to generate CO_2 (Chen et al., 2020; IPCC, 2006). Moreover, the formula and emission factor are taken from IPCC (2006) guidelines. GHG emissions from incineration disposal can be calculated as Eq.(2) (IPCC, 2006).

$$E_{Inc-CO_2} = MSW_{Inc} \cdot \sum_i \left(f_i \cdot dm_i \cdot CF_i \cdot FCF_i \cdot OF_i\right) \cdot 44/12\# \quad (2)$$

Where E_{Inc-CO_2} is the CO_2 emissions in the process of incineration. MSW_{Inc} is the amount of incinerated MSW. i is dry matter content in component i of the MSW incinerated. f_i is the fraction of carbon in the dry matter of component i. CF_i is the fossil carbon fraction in total carbon. OF_i is the oxidation factor, and the conversion factor from carbon to CO_2 is 44/12. The values of CO_2 emission factors from incineration are shown in Table S7 and S8 of SI.

During the biological disposal process, CH_4 and N_2O are generated from the organic matter in the MSW due to microbial degradation (Sanchez et al., 2015). Therefore, the emissions of CH_4 and N_2O are considered in the calculation of GHG from biological disposal. According to the calculation formula in the IPCC (2006) guidelines, activity data mainly include the disposal amount of each biological disposal method and the emission factors of CH_4 and N_2O (IPCC, 2006). GHG emissions from biological disposal can be calculated as Eqs. (3)–(4) (IPCC, 2006).

$$E_{Bio-CH_4} = \sum_j \left(MSW_j \cdot EF_j\right) \cdot 10^{-3}\# \quad (3)$$

$$E_{Bio-N_2O} = \sum_j \left(MSW_j \cdot \ EF_j\right) \cdot 10^{-3}\# \quad (4)$$

Where MSW_j is the disposal amount of *j* biological disposal methods. EF_j is the emission factor of *j* biological disposal methods. *j* refers to composting or anaerobic digestion. The detailed values are shown in Table S9 of SI.

2.3. The reduction of GHG emissions

The following methods are mainly considered to reduce GHG emissions from MSW, which include (1) power generation from anaerobic digestion and incineration; (2) fertilizer production from compost; (3) material recycling. Among them, power generation (incineration and anaerobic digestion) and fertilizer production (composting) are the main methods of MSW energy utilization, and material recycling reduces GHG emissions by reducing the production of raw materials. Waste paper, plastic, glass, and metal are the primary recyclables, which have great potential to reduce GHG emissions (El Hanandeh and El Zein, 2011; Franchetti and Kilaru, 2012; Michel Devadoss et al., 2021; Turner et al., 2015). GHG emission reduction can be calculated as formula (5)-(8).

$$E_{Ele-Inc} = MSW_{Inc} \cdot \frac{LHV}{3600kJ/kWh} \cdot R_1 \cdot EF_1\# \tag{5}$$

$$E_{Ele-AD} = E_{AD-CH_4}\left(\frac{99.6\% \cdot 50\% \cdot 50100}{3600} \cdot EF_1 - 2.75\right)\# \tag{6}$$

$$E_{Fer} = MSW_{Com} \cdot EF_2\# \tag{7}$$

$$E_{Mat} = MSW_{Rec} \cdot EF_3\# \tag{8}$$

Where $E_{Ele-Inc}$ and E_{Ele-AD} are CO_2 emission reductions from incineration and anaerobic digestion by power generation; *LHV* is the low heating value of MSW; R_1 is the power generation efficiency (Table S11 of SI); EF_1, EF_2, and EF_3 refer to CO_2 emission factors of power generation, fertilizer production, and material recycling (detailed values in Table S10 and S12 of SI); E_{Mat} and E_{Fer} refer to CO_2 emission reductions from material recycling and fertilizer production; MSW_{Inc} and MSW_{Rec} are the amount of MSW incinerated and recycled; E_{AD-CH_4} is the CH_4 emissions generated from anaerobic digestion, and the CH_4 release rate reaches 99.6% (Zhou et al., 2022).

2.4. Scenario analyzes

According to the different degrees of forced source separation, three scenarios were set to predict the future GHG emissions in the forced source separation process, including the Business-As-Usual Scenario (BAU), the New Policy Scenario (NP), and the Low-carbon Scenario (LC). Waste components, energy efficiency, and wet waste disposal capacity were considered to change factors, and it was assumed that Shanghai would achieve zero landfill waste in 2023. China has been making great efforts to develop new energy, and the electricity generation structure would mainly consist of coal, hydrogen, solar, and wind energy, accounting for 27.60%, 14.60%, 27.00%, and 21.00% in 2030, respectively, according to the forecast, the variation of the power grid emission factor was taken into account in the NP and LC Scenarios (Zhou et al., 2022). The GHG emission factors in different scenarios are in Tables S14 and S15 of SI. Regarding waste compositions, the correlation and the BP neural network models are used to predict the MSW generation, and the correlation analysis and prediction results are shown in Tables S17 and Fig. S3 of SI.

2.5. Data source

The activity data includes MSW disposal from facilities and MSW components, mainly from official government data, field survey data, and related literature. The generation and disposal amount data of MSW in Shanghai are taken from the *Shanghai Landscaping and City Appearance Statistical Yearbook* and *Shanghai Municipal Solid Waste Environmental Pollution Prevention and Control Information Announcement*. The composition and properties of MSW are obtained from the annual report published by Shanghai Environmental Engineering Design and Research Institute. The global warming potential (GWP) of CH_4 and N_2O is derived from the IPCC AR5 report (IPCC, 2013).

3. Results and discussions

3.1. GHG emissions pattern from waste sectors

3.1.1. GHG emissions

The direct GHG emissions from waste sectors in Shanghai from 2016 to 2021 are shown in Fig. 3, and it increased from 3.06 (2016) $MtCO_2$-eq to 3.92 (2018) $MtCO_2$-eq, with an average annual growth rate of 22.39%. And then, the direct GHG emission increased from 5.52 (2019) $MtCO_2$-eq to 9.25 (2021) $MtCO_2$-eq, with an annual growth rate of around 24.68%. The net GHG emission rose from 2.19 to 2.94 $MtCO_2$-eq from 2016 to 2021 and reached a peak of 3.18 $MtCO_2$-eq in 2020. And the per capita net GHG emissions have increased from 89 kg (2016) to 118 kg CO_2-eq (2021), with a peak of 128 kg CO_2-eq in 2020.

GHG emissions from incineration disposal increased from 1.28 $MtCO_2$-eq to 8.42 $MtCO_2$-eq from 2016 to 2021, accounting for 90.97% of GHG emissions from MSW disposal in 2021. Incineration became the largest MSW GHG emission source since 2017, since around 41.56% of MSW was disposed of in the incineration plant. In contrast to landfill and biological disposal, GHG emissions from landfill decreased from 1.70 (2016) $MtCO_2$-eq to 1.18 (2019) $MtCO_2$-eq, with the proportion decreasing from 55.70% to 21.45% of the total emissions. The landfill volume significantly reduced to 0.69 Mt and 0.80 Mt in 2020 and 2021, but the annual GHG emissions still reached 0.71 $MtCO_2$-eq because of the large amount of waste stored in landfills. The GHG emissions from biological disposal were 0.09 $MtCO_2$-eq on average. After the source separation, the waste disposal in Shanghai changed significantly, which around 5.21 Mt mixed waste incinerated in half of the year, while it increased to 7.09 Mt in the second half year, among which the volume of incineration, biological disposal, and recycling increased by 0.97, 0.45, and 0.50 Mt, respectively. Landfill disposal volume decreased from 2.01 Mt to 1.99 Mt. Due to the reduction of organic matter in the MSW components, the increase of GHG emissions from landfill disposal decreased from 0.13 $MtCO_2$-eq to 0.08 $MtCO_2$-eq, while GHG emissions from incineration disposal rose from 1.16 $MtCO_2$-eq to 3.23 $MtCO_2$-eq. GHG emissions from biological disposal were around 0.03 $MtCO_2$-eq.

3.1.2. GHG emissions reduction potential

The total reduction in GHG emissions rose from 0.87 (2016) to 6.30 (2021) $MtCO_2$-eq. In incineration disposal, waste to energy by incineration can reduce GHG emissions by reducing fossil fuel consumption, and the GHG emission reduction effect is more evident due to the improvement of the LHV after forced source separation (Wang et al., 2009). Before the forced source separation, the LHV of MSW was about 6600 kJ/kg, and the reduction in GHG emissions from incineration power generation was between 0.61 and 0.86 $MtCO_2$-eq, with an average of 0.22 t CO_2-eq per ton MSW. After July 2019, the LHV increased to 13,160 and 12,580 kJ/kg, which could reduce GHG emissions by 0.41 t CO_2-eq per ton MSW on average.

Material recycling, fertilizer production from compost, and power generation from anaerobic digestion are also the main ways of GHG emission reduction. Because of the increase in the amount of MSW recycling, GHG emissions reduction from MSW recycling increased from 0.20 (2016) to 3.17 (2021) $MtCO_2$-eq, among which the GHG emission reduction of MSW recycling before and after forced source separation in 2019 rose from 0.59 to 1.18 $MtCO_2$-eq. And the annual GHG emission reductions from fertilizer production from compost and power generation from anaerobic digestion were 0.06 $MtCO_2$-eq on average.

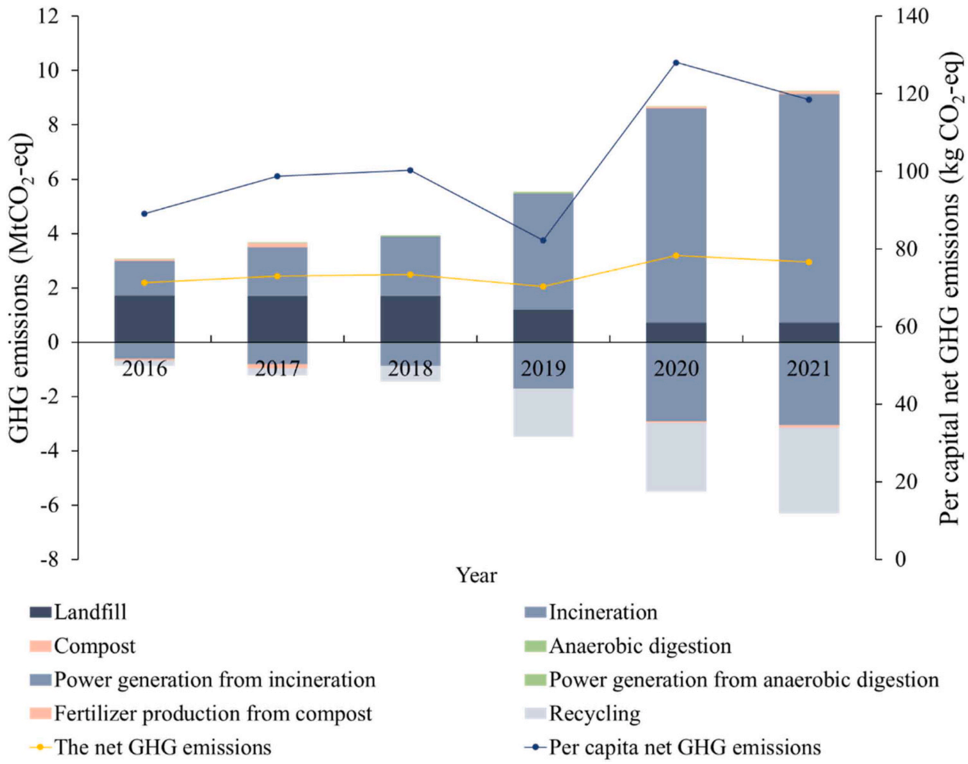

Fig. 3. The net GHG emissions, GHG emissions reduction and per capita net GHG emissions in Shanghai (2016–2021).
Note: In Fig. 3, the left axis used by the bar chart represents the changes in GHG emissions and emissions reductions, and the right axis used by the line chart represents the changes in per capita net GHG emissions.

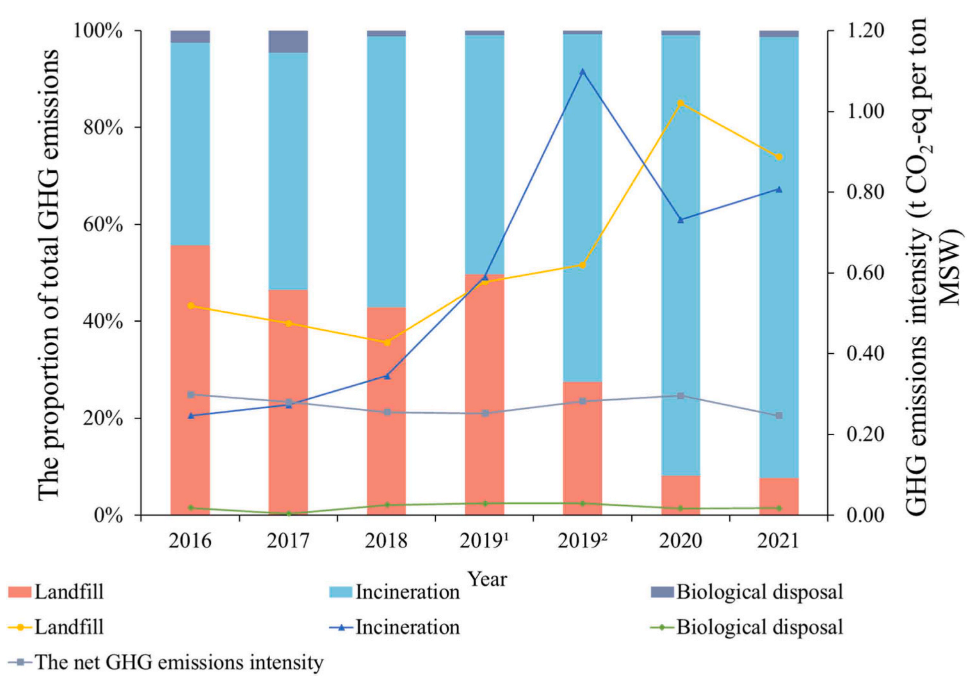

Fig. 4. The GHG emissions pattern in Shanghai (2016–2021).
Note: In Fig. 4, the left axis used for the bar chart represents the proportion of GHG emissions in different waste disposal methods, and the right axis used for the line chart represents the GHG emission intensity of different waste disposal methods.

3.2. GHG emission intensity

GHG emission intensity, defined as the GHG emissions per unit of MSW disposed of, can reflect the MSW disposal level (Li et al., 2022; Liu et al., 2021). The net GHG emission intensity decreased from 0.29 (2016) to 0.16 (2019) t CO_2-eq per ton MSW but increased to 0.29 and 0.24 t CO_2-eq per ton MSW in 2020 and 2021 due to the reduction in waste disposal.

Regarding landfill disposal, the GHG emission intensity dropped from 0.51 (2016) to 0.29 (2019) t CO_2-eq per ton MSW, but in 2020 and 2021, it reached 1.02 t and 0.88 t CO_2-eq per ton MSW, respectively. The reason was that despite the rapid reduction of landfill disposal volume, a large amount of CH_4 was still produced by the undercomposed organic matter in the landfill, which increased the GHG emission intensity significantly.

As the amount of incineration disposal and the LHV increased, the GHG emission intensity from incineration rose from 0.24 (2016) to 0.80 (2021) t CO_2-eq per ton MSW, of which GHG emission intensity increased from 0.59 to 1.10 t CO_2-eq per ton MSW before and after forced source separation. The GHG emission intensity of biological disposal was within 0.03 t CO_2-eq per ton MSW.

3.3. Scenario analysis

The BP neural network model was used to predict MSW production based on the data on MSW production and social-economic factors in Shanghai from 2003 to 2015, the detailed information can be seen in Section 3 of SI, and the results are shown in Fig. 5. It could be found that the amount of MSW production in Shanghai would reach 14.92 Mt in 2030, and the amount of waste recycling would reach 3.28 Mt, accounting for 28% of the total waste production. Dry and wet waste would reach 6.98 Mt and 4.65 Mt, respectively, with a ratio of 3:2.

3.3.1. BAU scenario

In the BAU scenario, since it was assumed that the wet waste disposal capacity would remain at 6380 t/d, the annual wet waste disposal would be stable at about 2.23 Mt, accounting for only 48% of the wet waste disposal volume. Due to insufficient wet waste disposal capacity, a large amount of wet waste would be incineration disposal. Shanghai was expected to achieve zero landfills for raw MSW by 2023, so incineration had become the primary dry waste disposal method. The amount of waste incinerated in 2030 was expected to reach 9.40 Mt, accounting for 63% of total waste production.

And without changes in wet waste disposal mode, power generation efficiency, and waste components, it could be seen that with the increase of waste incineration, the net GHG emissions were still on the rise and would reach 4.17 $MtCO_2$-eq in 2030, an increase of 1.23 $MtCO_2$-eq compared with 2021. And the proportion of incineration emissions would eventually reach about 95%, and landfill and biological disposal account for 4.00% and 1.22% of total GHG emissions. In comparison, net GHG emission intensity would stabilize at 0.28 t CO_2-eq per ton MSW.

3.3.2. NP scenario

In the NP scenario, the disposal capacity of wet waste would reach 11,350 t/d, and the annual disposal volume of wet waste would reach 3.97 Mt, which would be able to dispose of 85% of the wet waste. In the government plan, Shanghai would build 7 wet waste disposal facilities in the future. With the improvement of wet waste disposal capacity, waste incineration peaked at 7.92 Mt in 2023 and dropped to 7.66 Mt in 2030, accounting for 51%.

The simulation results showed that GHG emissions would decrease in Shanghai when the wet waste disposal capacity and the power generation efficiency would increase to 11,350 t/d and 25%, and the proportion of waste plastic dropped by 10%. The result showed that with the improvement of wet waste disposal capacity, the net GHG emissions would eventually rise to 3.21 $MtCO_2$-eq in 2030 and peak at 3.72 $MtCO_2$-eq in 2025, and the net GHG emission intensity would decrease to 0.21 t CO_2-eq per ton MSW. The net GHG emissions from incineration and biological disposal would eventually reach 6.49 and 0.07 $MtCO_2$-eq, and the GHG emissions reduction from recycling would be increased to 3.96 $MtCO_2$-eq.

3.3.3. LC scenario

Higher wet waste disposal capacity (12,000 t/d) and incineration power efficiency (30%), and a lower proportion of waste plastic (38.30%) were set in the LC scenario. The annual volume of wet waste disposal would reach 4.20 Mt, accounting for around 90% of wet waste. The incineration disposal volume would be decreased to 7.43 Mt in 2030, lower than 7.58 (2021) Mt. The mode of total dry waste incineration and a small amount of wet waste incineration would be achieved.

The simulation showed that net GHG emissions and net GHG emissions intensity would eventually decrease to 1.82 $MtCO_2$-eq and 0.12 t CO_2-eq per ton MSW, respectively. Due to the reduction of wet waste incineration, the GHG emissions from incineration would drop to 7.65 $MtCO_2$-eq, lower than 7.89 $MtCO_2$-eq in 2020, and the proportion of GHG emissions from biological disposal would reach 3.40%. In the NP and LC scenario, Shanghai had the opportunity to achieve a carbon peak in the waste sector before 2030.

4. Conclusions

From 2016–2021, the MSW disposal amount in Shanghai increased from 7.35 Mt to 11.94 Mt, and incineration has become the main method of MSW disposal in Shanghai. Under the waste classification policy, the

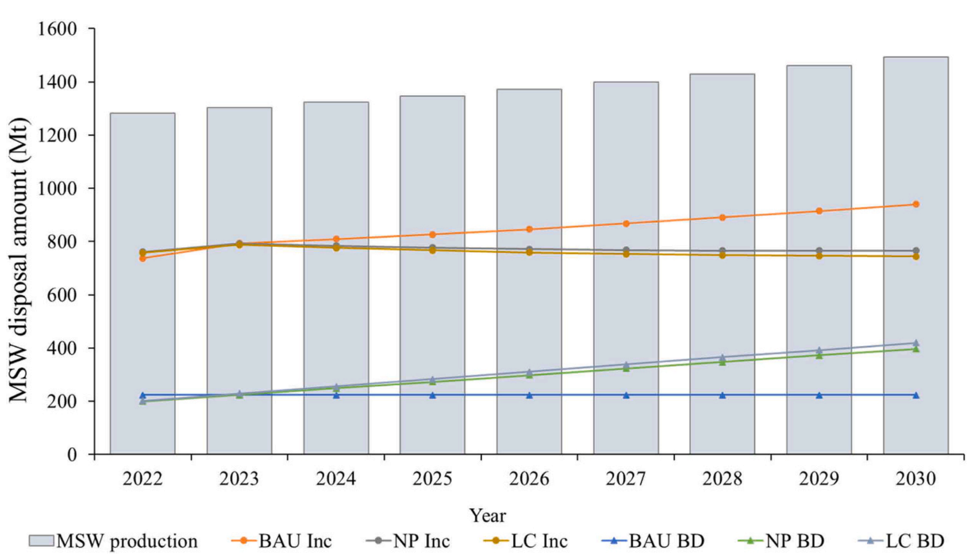

Fig. 5. MSW disposal amount under different scenarios.

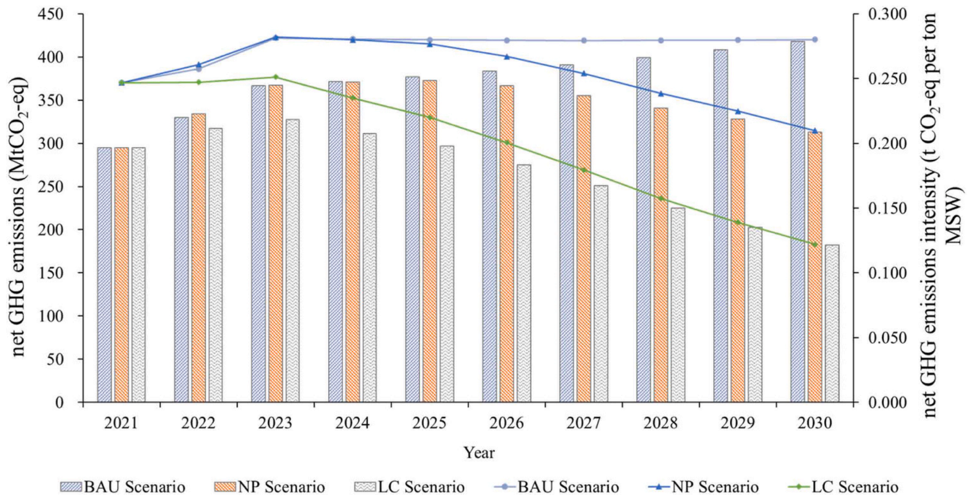

Fig. 6. net GHG emissions and GHG emission intensity under different scenarios.
Note: In Fig. 6, the left axis used for the bar chart shows the net GHG emissions under different scenarios, and the right axis used for the line chart shows the net GHG emission intensity under different scenarios.

composition and physicochemical properties of MSW have changed. Before waste classification, the waste entering the terminal MSW disposal facilities in Shanghai was mixed waste, which was mainly composed of kitchen waste, paper and plastics. After waste classification, MSW was divided into dry waste and wet waste, of which dry waste is mainly composed of rubber and waste plastic, accounting for 41.57%, and the organic matter content in dry waste was significantly reduced, from 77.08% to 47.53%. The proportion of organic matter in wet waste has reached 99.58%. In addition, the LHV of waste increased from 6600 kJ/kg (mixed waste) to 12580 and 13525 kJ/kg (dry waste), while the water content of MSW decreased from 56.96% (mixed waste) to 36.22% (dry waste).

The IPCC bottom-up method was used to calculate the GHG emissions in the MSW disposal process of Shanghai. From 2016–2021, the net GHG emissions from waste disposal in Shanghai increased from 2.19 $MtCO_2$-eq to 2.94 $MtCO_2$-eq, and the net GHG emission intensity decreased from 0.29 to 0.24 t CO_2-eq per ton MSW. Three scenarios were set up to analyze the change in GHG emission in Shanghai during the process of forced source separation, and the results showed that with the improvement of wet waste disposal capacity, incineration power generation efficiency, and the reduction of waste plastics proportion in waste components, the GHG emission intensity of the waste sector decreased gradually. According to this study, in the process of forced source separation, increasing the construction of biological disposal facilities, improving the efficiency of incineration power generation, and further reducing the proportion of plastic waste in waste components are all effective strategies to reduce GHG emissions in the waste sector.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.psep.2023.10.006.

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