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Research on Greenhouse Gas Emission Characteristics and Emission Mitigation Potential of Municipal Solid Waste Treatment in Beijing

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Abstract: Greenhouse gas (GHG) emissions are a significant cause of climate change, and municipal solid waste (MSW) is an important source of GHG emissions. In this study, GHG emissions from MSW treatment in Beijing during 2006–2019 were accounted, basing on the Intergovernmental Panel on Climate Change (IPCC) inventory model; the influencing factors affecting GHG emissions were analyzed by the logarithmic mean Divisia index (LMDI) model combined with the extended Kaya identity, and the GHG mitigation potential were explored based on different MSW management policy contexts. The results showed that the GHG emissions from MSW treatment in Beijing increased from 3.62 Mt CO_2e in 2006 to 6.57 Mt CO_2e in 2019, with an average annual growth rate (AAGR) of 4.68%, of which 89.34–99.36% was CH_4. Moreover, the driving factors of GHG emissions from MSW treatment were, in descending order: economic output (EO), GHG emission intensity (EI), population size (P), and urbanization rate (U). The inhibiting factors were, in descending order: MSW treatment pattern (TP) and MSW treatment intensity (TI). Furthermore, compared with the BAU (business–as–usual) scenario, the GHG mitigation potential of the MSW classification and the population control scenario were 35.79% and 0.51%, respectively, by 2030.

Keywords: municipal solid waste treatment; greenhouse gas emission; emission reduction potential; scenario analysis; Beijing

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1. Introduction

The continuous acceleration of the urbanization process and economic development have contributed to an increasing amount of municipal solid waste (MSW), and China's MSW treatment amount has increased at an average annual rate of 5.4% since the 1980s [1]. The process of MSW treatment inevitably emits a large amount of greenhouse gases (GHG) [2]. The Climate Change 2007 Synthesis Report published by the Intergovernmental Panel on Climate Change (IPCC) explicitly proposes to calculate GHG emissions from post-consumer waste as a separate object [3]. Several studies have shown that the MSW sector is the third largest contributor to global non-carbon dioxide (non-CO_2) GHG emissions [4], and GHG emissions from MSW treatment accounted for 3% of GHG emissions [5–9]. According to China's Climate Change Information Circular, GHG emissions from MSW treatment were 110, 132, and 195 million tons CO_2-equivalent (Mt CO_2e) in 2005, 2010 and 2014, respectively [10,11]. Bian et al. [12] found that GHG emissions from MSW treatment reached 356 Mt CO_2e in 2019. China is actively reducing GHG emissions in all aspects to achieve its strategic goals of peaking CO_2 emissions by 2030 and achieving carbon neutrality by 2060, and strengthening the management of MSW treatment is one of the important ways to reduce GHG emissions.

GHG emissions are an important research component of MSW management. Existing studies have focused on accounting for GHG emissions from MSW treatment, and on emission mitigation measures at national and city levels. A comprehensive and accurate estimation of GHG emissions from MSW treatment should be a prerequisite for designing appropriate GHG reduction policies. The relevant studies are shown in Table 1. Life cycle assessment (LCA), the mass balance (MB) method of the Intergovernmental Panel on Climate Change (IPCC), the first-order decay (FOD) model of IPCC, and the modified triangular method (TM), have been used to calculate GHG emissions from MSW sanitary landfill, incineration and composting treatment.

Table 1. A study of the literature related to the accounting of greenhouse gases (GHG) emissions from municipal solid waste (MSW) treatment. (Adapted with permission from Refs. [12–22]).

Model	Area	Time	Found
MB	China (1997)	1990–1994	Methane emissions were approximately 2.4 million to 3.2 million tons, and the share of landfilled MSW will directly affect the accuracy of the emissions inventory.
LCA	U.S.A. (2002)	1974–1997	GHG emissions from MSW management were estimated to be 72 million tons CO_2e in 1974, and 1600 million tons CO_2e in 1997.
MB, TM	India (2004)	1980–1999	The proposed triangular model landfill methane emission calculation method was more realistic and could be well used for estimation, and the methane emissions varied between 119.01 Gg in 1980 and 400.66 Gg in 1999.
LandGEM 3.02	India (2014)	2001–2020	An amount of 88.44% of the total greenhouse gas emissions were CH_4 and the rest were CO_2.
FOD	Italy (2016)	1990–2014	The CH_4 emission in 2017 was 107.7 Mt.
FOD	U.S.A. (2017)	1990–2014	CH_4 emissions from landfills decreased by 71.8 Mt CO_2e from 1990 to 2017.
LCA	Nottingham, England (2019)	2001–2017	GHG emissions from MSW management were reduced by 0.21–1.08 t CO_2e due to improvements in waste collection, treatment and material recovery, and waste prevention.
FOD	Malaysia (2021)	2016	GHG emissions released from solid waste disposal sites (SWDS) were 6.89 Mt CO_2e in 2016, and are projected to increase to 9.99 Mt CO_2e in 2030.
FOD	Shanghai, China (2021)	2005–2015	Landfills accounted for 81.88% of total GHG emissions from 2005 to 2015, and incineration had lower emission intensity than landfills and composting.
LCA	Tehran, Iran (2021)	-	Daily GHG emissions from incineration and landfills were estimated at 4499.07 and 92,170.30 kg CO_2e.
FOD	China (2022)	2006–2019	Total GHG emissions from the waste sector increased from just under 110 Mt CO_2e in 2006, to 356 Mt CO_2e in 2019.

In order to develop strategic emission mitigation measures, scholars mainly focused on comparing the effects of different forms of MSW treatment methods on GHG mitigation potential. Studies found that sanitary landfills emitted the most GHG, and changing the MSW treatment method from sanitary landfills to incineration was an effective measure to reduce total GHG emissions, as incineration of MSW as a renewable fuel can reduce the use of fossil fuel [23–25]. Pérez et al. [26] found that switching from landfill to incineration was an effective measure to reduce total GHG emissions by 11.3%. However, some studies have also pointed out that MSW incineration in China does not reduce GHG emissions, but rather emits GHG [27,28]. In addition, recycling and sorting of MSW was also found to be a key driver of GHG emissions reduction, which helps to reduce GHG emissions, acid rain deposition and dioxin emissions [29,30].

The above studies help to understand GHG emissions and select more feasible methods for MSW treatment, to minimize GHG emissions. However, the following gaps exist in the current literature: (i) there are still large differences and uncertainties in accounting GHG emissions from MSW treatment due to the difference of MSW treatment structures and MSW components, and the lack of research on emission factors and key parameters that match the actual situation; and (ii) studies on emission reduction measures usually take a single and static perspective, while ignoring the relevant influencing factors of GHG emissions and management policy implications.

This study used Beijing as the research object and calculated GHG emissions from MSW treatment during 2006–2019 using the estimation formula drawn from the Intergovernmental Panel on Climate Change (IPCC). The influencing factors of GHG emissions from MSW treatment were analyzed by the logarithmic mean Divisia index (LMDI) model combined with the extended Kaya identity. Furthermore, we combined the changes in the parameters of influencing factors under the policies related to MSW classification and population control in Beijing, to analyze the potential of GHG mitigation from MSW treatment, with a view to providing a theoretical basis for MSW management, GHG emission control and decision-making.

2. Materials and Methods

2.1. Overview of MSW Treatment in Beijing

Beijing is the capital of China and the second largest city in the country, with an MSW generation of 10.11 Mt and a harmless rate of MSW reaching 100% in 2019. According to the data published by the Beijing Urban Management Commission [31], Beijing has 27 MSW treatment facilities, including 9 sanitary landfills, 10 incineration plants and 8 composting plants.

MSW treatment in Beijing is still based on the dominant methods of sanitary landfill, incineration, and composting. As shown in Figure 1, the MSW treatment pattern (ratio of MSW sanitary landfilled to incinerated to composted) was 14:73:16 at the end of the 11th Five-Year Plan period, with sanitary landfills occupying the main position of MSW treatment due to its low cost and mature technology [32]. At the end of the 12th Five-Year Plan period, the MSW treatment pattern was 36:44:20, which saw the change from "sanitary landfill" to "incineration" as the predominant treatment method. In the 2019 during the 13th Five-Year Plan period, the MSW treatment pattern was 24:50:26, forming a comprehensive pattern of "incineration as the main pattern, composting and sanitary landfill as a supplement". It can be seen that MSW treatment has mainly developed in the direction of incineration, and the sanitary landfill rate of MSW generally declined from 2006 to 2019 in Beijing.

2.2. Methodology for Accounting GHG Emissions from MSW Treatment

2.2.1. Sanitary Landfill

The main components of landfill gas in sanitary landfill are methane (CH_4) and CO_2. CO_2 is mainly derived from the decomposition of organic matter, which is a biological cause, so it is not included in the GHG emission inventory. Only the amount of CH_4 is counted in the GHG inventory for sanitary landfill.

The study used the FOD model (see Equations (1)–(3)) recommended by the Intergovernmental Panel on Climate Change (IPCC). Informal landfills and dumping were still very common in Beijing before 1990, and many landfills were not specially designed or took any engineering measures, lacking bottom and side impermeable layers and a top cover layer. The North Shenshu Comprehensive Waste Treatment Plant and Shijingshan Simple Waste Treatment Plant began operation in 1991 [33], and therefore 1991 was set as the baseline year for Beijing commencing the existing of sanitary landfills. According to the IPCC Fifth

Assessment Report, CH_4 emissions are converted to CO_2 equivalent at 28 times that of CO_2 [34].

$$E_{CH_4} = MSW_L * \sum_{i=1}^{n} L_{0i}\left(e^{-(T-1)\cdot K_i} - e^{-T\cdot K_i}\right) * (1-R) * (1-OX) \tag{1}$$

$$L_{0i} = MCF * DOC * DOC_F * F * 16/12 \tag{2}$$

$$DOC = \sum_{i=1}^{4} DOC_i \times W_i \tag{3}$$

where E_{CH4} is CH_4 emission from MSW sanitary landfill; MSW_L is the amount of MSW sanitary landfilled; L_{0i} is the potential methane production capacity of type i in MSW; K_i is the reaction constant; R is the methane recovery rate; OX is the methane oxidation factor; MCF is the correction factor; DOC is the proportion of degradable organic matter; DOC_F is the fraction of dissimilated DOC; F is the fraction of methane in landfill gas; DOC_i is the proportion of degradable organic carbon in a physical component i; and W_i is the proportion of type i in MSW.

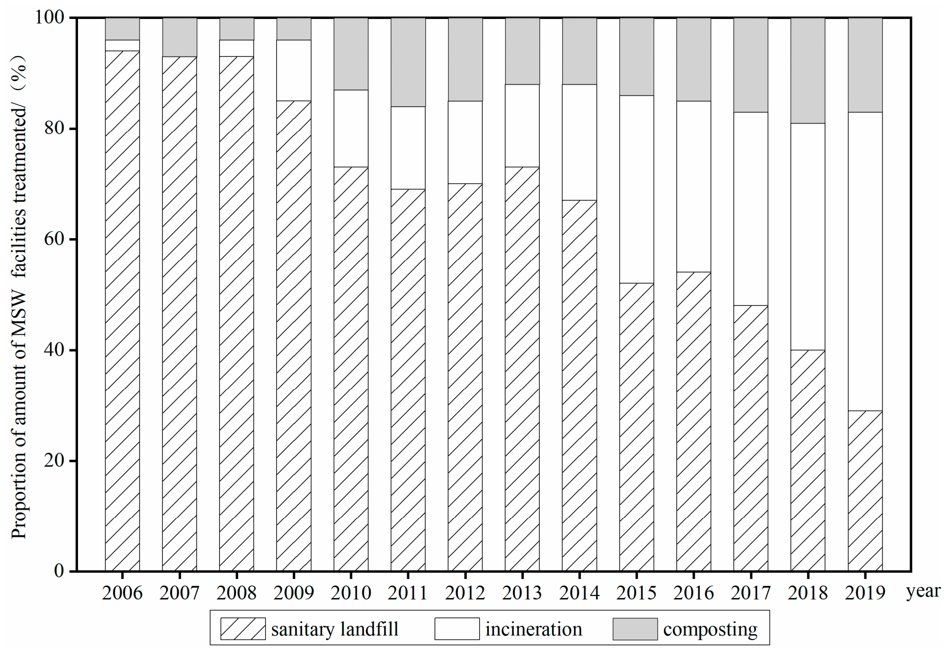

Figure 1. Municipal solid waste (MSW) treatment pattern during the period 2006–2019 in Beijing.

According to the recommended default values by the IPCC, in terms of OX, DOC_F, F, R is 0.1, 0.5, 0.5, 0, and the DOC_i, K_i for different types of waste in the wet base state are shown in Table 2. W_i is taken from values in the literature.

Table 2. DOC_i and K_i of physical components in MSW.

Type	Food Waste	Paper	Textile	Wood
DOC_i	0.15	0.40	0.24	0.43
K_i	0.18	0.06	0.06	0.03

2.2.2. Incineration

The GHG emissions from MSW incineration are mainly CO_2 and small amounts of CH_4 and nitrous oxide (N_2O). CO_2, CH_4 and N_2O emissions from MSW incineration were calculated with reference to the IPCC (see Equations (4) and (5)). According to the IPCC

Fifth Assessment Report, the updated value of global warming potential for N_2O is 265 times the global warming potential of CO_2.

$$E_{CO_2} = MSW_I \times \sum_j (WF_j \times dm_j \times CF_j \times FCF_j \times OF_j) \times 44/12 \quad (4)$$

where E_{CO2} is the CO_2 emissions from MSW incineration; MSW_I is the amount of MSW incinerated; j is the composition of the incinerated MSW that can be combusted and can release CO_2, including the five components of kitchen waste, paper, plastic, textiles, and wood; WF_j is the fraction of MSW type of component j; dm_j is the dry matter content of component j; CF_j is the fraction of carbon in the dry matter of component j; FCF_j is the fraction of fossil carbon of component j; OF_j is the oxidation factor; and 44/12 is the conversion ratio from C to CO_2.

The values dm_j, CF_j and FCF_j are taken from the recommended values of the Beijing local standard Greenhouse gas emission accounting guide for domestic waste incineration enterprises (DB11/T 1416–2017) shown in Table 3, and OF_j was taken from the IPCC recommended default value of 95%. WF_i was taken from values from the literature.

$$E_{CH_4/N_2O} = MSW_I \times EF_k \times 10^{-6} \quad (5)$$

where $E_{CH4/N2O}$ is CH_4 or N_2O emissions from MSW incineration; MSW_I is the amount of MSW incinerated, Mt; and EF_k is the incinerated emission factor. According to the recommended values by the IPCC, the emission factor of compost is 6.5 kg/t MSW for CH_4, and 0.06 kg/t MSW for N_2O.

Table 3. dm_j, CF_j and FCF_j of physical components in MSW.

Type	Food Waste	Paper	Plastic	Textile	Wood
dm_j	0.62	0.31	0.32	0.52	0.28
CF_j	0.50	0.46	0.78	0.61	0.53
FCF_j	0.11	0.09	0.68	0.52	0.18

The net GHG emissions from incineration treatment are the total GHG emissions minus the power generation emission reductions, and the power generation emission reductions are calculated in Equation (6) [35,36].

$$E_{\text{avoiding}} = AD_e \times EF_e \times MSW_I \quad (6)$$

where E_{avoiding} is GHG emissions reduction from electricity generation; AD_e is the mass of on-grid energy from incineration (MWh), taking the literature value of 298.07×10^{-3}, and EF_e is electricity carbon emission factor, taking the literature value of 0.7598 (tCO_2/MWh) [36].

2.2.3. Composting

The study used the methodology recommended by the IPCC to account for GHG emissions from MSW composting processes (see Equation (7)).

$$E_{CH_4/N_2O} = MSW_C \times EF_C \times 10^{-3} \quad (7)$$

where $E_{CH4/N2O}$ is CH_4 or N_2O emissions from MSW composting; $MSWc$ is the amount of MSW composted; and EF_c is the compost emission factor. According to the recommended values by the IPCC, the emission factor of compost is 4 kg/t MSW for CH_4, and 0.3 kg/t MSW for N_2O.

2.3. Analysis Method of GHG Emission Influencing Factors of MSW Treatment

Referring to the decomposition of GHG emission impact of MSW treatment proposed by Wang et al. [37–39], the logarithmic mean Divisia index (LMDI) model combined with the extended Kaya identity [40] (see Equation (8)) were used to decompose the GHG emission impact factors. Each influencing factor is defined in Table 4.

$$\begin{aligned} GHG &= \sum_{i=1}^{3} GHG_i = \sum_{i=1}^{3} \frac{GHG_i}{G_i} \times \frac{G_i}{G} \times \frac{G}{GDP} \times \frac{GDP}{UP} \times \frac{UP}{P} \times P \\ &= \sum_{i=1}^{3} EI_i \times TP_i \times TI \times EO \times U \times P \end{aligned} \tag{8}$$

where i is the three treatment methods of MSW, sanitary landfill, incineration and composting; G_i is the amount of MSW treatment method i; G is the total MSW treatment amount; GDP is the city's gross domestic product; UP is the number of urban populations; and P is the regional population size.

Table 4. Definitions of influencing factors of GHG emissions from MSW treatment.

Factors	Definition
EI_i	GHG emission intensity, which is the GHG emissions per unit of MSW treated in MSW treatment method i.
TP_i	MSW treatment pattern, which is the proportion of MSW treatment i, to total MSW treatment.
TI	MSW treatment intensity, which is the amount of MSW treatment per unit of GDP.
EO	Economic output, which is GDP per capita per year.
U	Urbanization ratio, which is the ratio of urban population to total population size.
P	Population size, which is the population size, indicating the effect of population size on GHG emissions from MSW treatment.

Between the target (T) and the base (B), the GHG emissions change from MSW treatment can be expressed by the LMDI model, as shown in Equation (9). In Equations (10)–(15), ΔEI_i, ΔTP_i, ΔTI, ΔEO, ΔU, and ΔP are the contributions of EI_i, TP_i, TI, EO, U, and P to ΔGHG, respectively. A positive value indicates that the influencing factor has a driving effect on GHG emissions, while a negative value indicates that the influencing factor has a suppressing effect on GHG emissions.

$$\Delta GHG = GHG^t - GHG^b = \Delta EI + \Delta TP + \Delta TI + \Delta EO + \Delta U + \Delta P \tag{9}$$

$$\Delta EI = \sum_i \frac{GHG_i^t - GHG_i^b}{lnGHG_i^t - lnGHG_i^b} ln\frac{EI_i^t}{EI_i^b} \tag{10}$$

$$\Delta TP = \sum_i \frac{GHG_i^t - GHG_i^b}{lnGHG_i^t - lnGHG_i^b} ln\frac{TP_i^t}{TP_i^b} \tag{11}$$

$$\Delta TI = \frac{GHG^t - GHG^b}{lnGHG^t - lnGHG^b} ln\frac{TI^t}{TI^b} \tag{12}$$

$$\Delta EO = \frac{GHG^t - GHG^b}{lnGHG^t - lnGHG^b} ln\frac{EO^t}{EO^b} \tag{13}$$

$$\Delta U = \frac{GHG^t - GHG^b}{lnGHG^t - lnGHG^b} ln\frac{U^t}{U^b} \tag{14}$$

$$\Delta P = \frac{GHG^t - GHG^b}{lnGHG^t - lnGHG^b} ln\frac{P^t}{P^b} \tag{15}$$

The relative contribution of each influencing factor to the amount of change in GHG emissions from MSW treatment are shown as follows: $\mathrm{R}(EI) = \frac{\Delta EI}{\Delta GHG}$, $\mathrm{R}(TP) = \frac{\Delta TP}{\Delta GHG}$, $\mathrm{R}(TI) = \frac{\Delta TI}{\Delta GHG}$, $\mathrm{R}(EO) = \frac{\Delta EO}{\Delta GHG}$, $\mathrm{R}(U) = \frac{\Delta U}{\Delta GHG}$, $\mathrm{R}(P) = \frac{\Delta P}{\Delta GHG}$.

2.4. Scenario Assumptions

Scenario analysis helps to study the development of MSW management over time under a specific set of conditions. In order to demonstrate the GHG reduction potential of the MSW management in Beijing, three scenarios were designed in the study: the BAU (business–as–usual) scenario, the MSW classification scenario, and the population control scenario. The flow chart of GHG emissions from MSW treatment is shown in Figure 2, and the assumptions of MSW management scenarios are shown in Table 5.

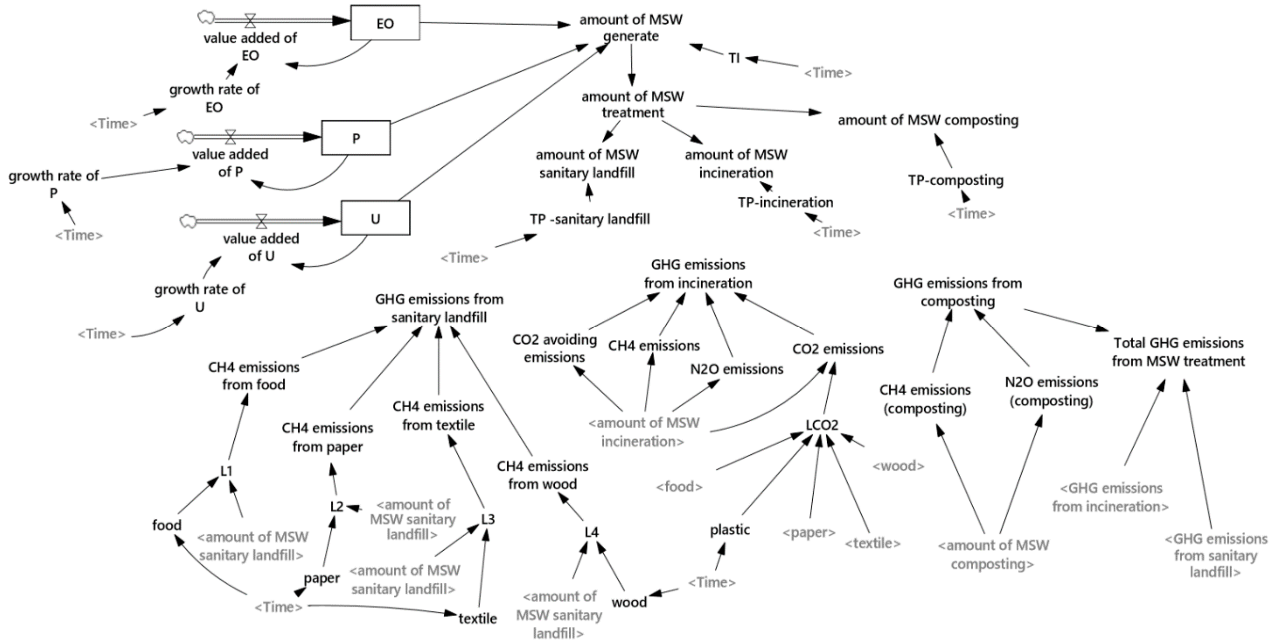

Figure 2. MSW treatment GHG emission system flow. Note: < . . . > are shadow variables, which are used to refer to already existing parameters.

Table 5. MSW treatment scenario assumptions (2020–2030).

Scenario	Factors	Scenario Assumptions
BAU scenario	EI, TP, TI, EO, U, P	According to the Beijing Urban Master Plan (2016–2035), assume economic output growth rate of 5%, and population size increase of 100,000 per year. According to the current situation of Beijing's MSW treatment capacity and the 14th Five-Year Plan for the Development of MSW Separation and Treatment Facilities, assume an incineration rate of 65%, sanitary landfill rate of 15%, and composting rate of 20% for 2020–2030, and with no change in urbanization rate and GHG emission intensity.
Classification of MSW scenario	EI	According to the Beijing Urban Management Development Plan for the 14th Five-Year Period, assume 30% reduction in food entering sanitary landfill and incineration plants. According to the target of 37.5% MSW recycling rate, assume 7.5% reduction in paper.
	TP	According to the Beijing Urban Management Development Plan for the 14th Five-Year Period, assume an incineration rate of 70%, sanitary landfill rate of 0% and composting rate of 30%, with no change in GHG emission intensity.
	TI	Reduction of MSW intensity (TI) by 7.5% from the original base in 2020–2030.
	EO, U, P	Consistency with the BAU scenario.
Population control scenario	P	According to the literature study, Beijing has a proper population of 21.52 million people [41], assume with no change in population size.
	EI, TP, TI, EO, U	Consistency with the BAU scenario.

2.5. Data Source

The statistical values of MSW treatment per facility (sanitary landfill, incineration, and composting), population size, and GDP, were collected from the China City Statistical Yearbook (2006–2019) [42] and which are shown in Table A1. The physical components of MSW in Beijing from 2006 to 2019 were obtained from literature research and which are shown in Table A2 (Adapted with permission from Refs. [24,43–45]).

3. Results

3.1. GHG Emission Characteristics from MSW Treatment in Beijing

As shown in Figure 3, GHG emissions from MSW treatment in Beijing more than doubled during the period 2006–2019, which increased from 3.62 Mt CO_2e in 2006 to 6.57 Mt CO_2e in 2019, with an average annual growth rate (AAGR) of 4.68%. The change of GHG emissions from MSW treatment in Beijing can be divided into two stages: the period of 2006–2010, which was the stage of rapid growth of GHG emissions, with an average annual growth rate (AAGR) of 9.68%; and the period of 2011–2019, which was the stage of slow growth of GHG emissions, with an average annual growth rate (AAGR) of 2.49%. The changes in these two stages may be due to the implementation of 600 MSW classification pilot projects and MSW reduction measures such as "clean vegetables in the city", in Beijing in 2010.

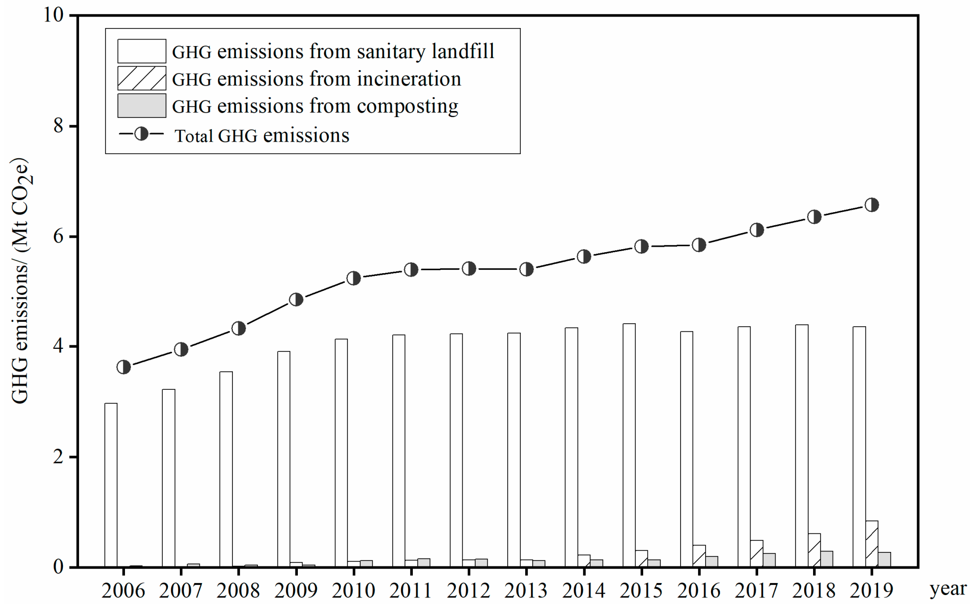

Figure 3. GHG emissions from MSW treatment during the period 2006–2019 in Beijing.

In terms of proportion of GHG, CH_4 contributed the most to GHG emissions from MSW treatment. As shown in Figure 4, the percentage of CH_4 emissions from MSW treatment decreased from 99.36% in 2006 to 89.34% in 2019, with an average annual reduction rate of 0.81%. CO_2 was the second highest contributor to GHG emissions from MSW treatment, increasing from 0.19% in 2006 to 8.01% in 2019, with an average annual growth rate of 33.09%. N_2O contributed the least to GHG emissions from MSW treatment in Beijing, accounting for 0.45–2.72%.

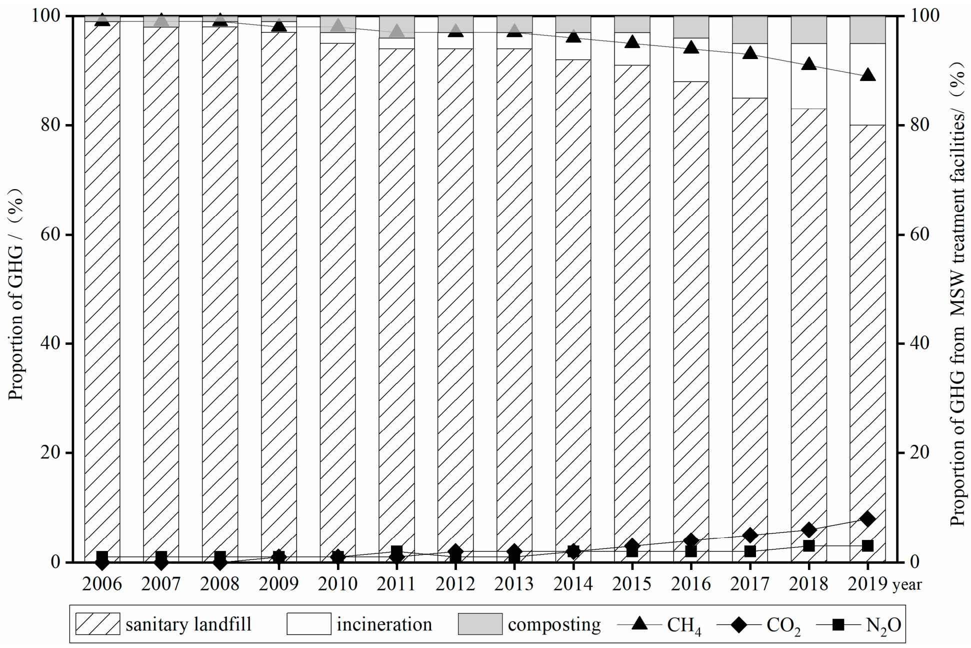

Figure 4. Share of GHG and GHG emissions from MSW treatment facilities during the period 2006–2019 in Beijing.

In terms of the proportion of GHG emissions from MSW treatment facilities, sanitary landfill was the main source of GHG emissions from MSW treatment in Beijing. As shown in Figure 4, the percentage of sanitary landfill emissions decreased from 98.56% in 2006 to 79.61% in 2019, with an average annual reduction rate of 1.63%, and GHG emission intensity of sanitary landfills increased from 0.76 tCO_2e/t MSW in 2006, to 1.79 tCO_2e/t MSW in 2019. Incineration was the second largest source of GHG emissions from MSW treatment in Beijing, and the percentage of incineration emissions increased from 0.41% in 2006 to 15.53% in 2019, with an average annual growth rate of 32.19%. The net GHG emission intensity of incineration plants after incineration for power generation increased from 0.15 tCO_2e/t MSW in 2006, to 0.18 tCO_2e/t MSW in 2019. Composting was the lowest source of GHG emissions from MSW treatment in Beijing, accounting for 1.04–5.48%, and the greenhouse gas emission intensity of composting treatment plants was about 0.19 tCO_2e/t MSW, which may be due to the limited application of composting by-products (e.g., organic fertilizer).

3.2. Analysis of GHG Emission Influencing Factors of MSW Treatment

As is shown in Figure 5 and Table 6, the contribution value and rate of each influencing factor of GHG emissions from MSW treatment in Beijing from 2006 to 2019 were calculated by the logarithmic mean Divisia index (LMDI) model combined with the extended Kaya identity, and using the intervals of the adjacent year as samples of changes.

Economic output (EO) was the leading contributor, which increased by 0.61 Mt CO_2e, with a contribution rate of 206.29%. EO rapidly increased from RMB 60,900/capita in 2006, to RMB 190,000/capita in 2019, with an average annual growth rate of 9.13%. Due to the transformation of living habits and consumption structure to a high-carbon model as a result of the improvement of people's living standards, an increase in per capita MSW generation and the proportion of high-carbon MSW has followed.

GHG emissions intensity (EI) was the second highest contributor, which increased by 0.44 Mt CO_2e, with a contribution rate of 149.06%. EI increased from 0.73 t CO_2/t MSW to 0.65 t CO_2/t MSW, which may be due to changes in people's lifestyles, the decreasing prices of recycled resources, and the increasing proportion of high-carbon MSW entering MSW treatment facilities leading to an increase in EI for sanitary landfill and incineration treatment, which drives increasing GHG emissions from MSW treatment.

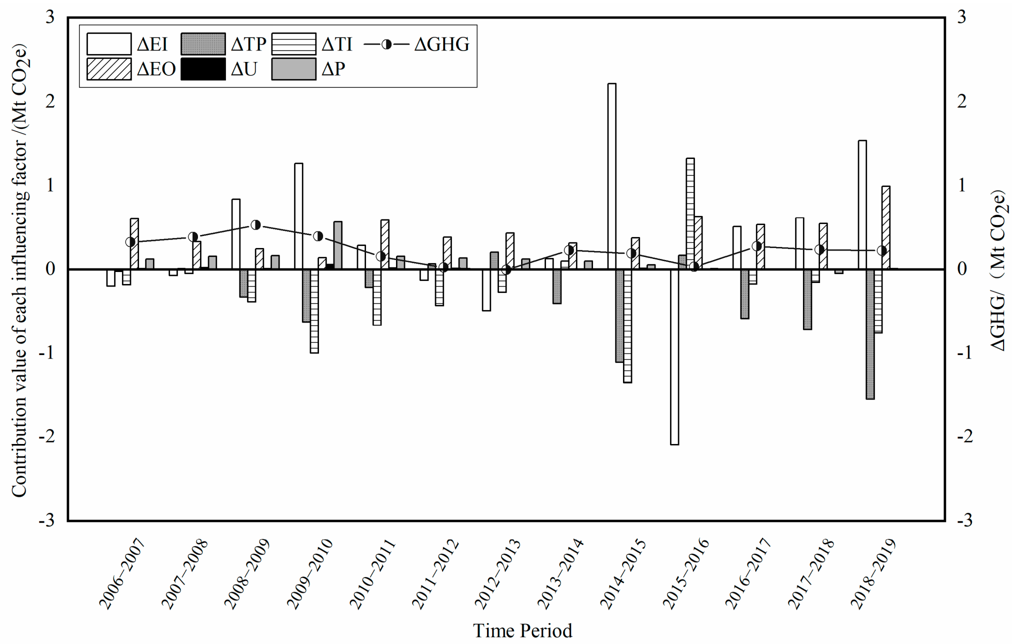

Figure 5. Contribution value of each influencing factor of MSW treatment to GHG emissions in Beijing from 2006 to 2019.

Table 6. Contribution rate of each influencing factor of MSW treatment to GHG emissions in Beijing (%).

Time Period	R (EI)	R (TP)	R (TI)	R (EO)	R (U)	R (P)
2006–2010	112.63	−60.34	−100.03	80.71	5.44	61.59
2011–2019	193.63	−313.62	−180.89	359.93	3.18	37.77
2006–2019	149.06	−174.25	−136.40	206.29	4.43	50.88

Population size (P) was the third highest contributor, which increased by 0.15 Mt CO_2e, with a contribution rate of 50.88%. A larger population size generates more MSW, and P increased from 15.81 million in 2006 to 21.73 million in 2016, with an annual average increase of 3.23%, which contributed to GHG emissions from MSW treatment. Conversely, P decreased from 21.71 million to 21.54 million from 2017 to 2019, which caused a reduction of GHG emissions.

Urbanization rate (U) was the lowest driving contributor, which increased by 0.01 Mt CO_2e, with a contribution rate of 4.43%. U slowly increased from 84.31% in 2006 to 86.58% in 2019, with an average annual growth rate of 0.20%, due to Beijing's higher urbanization level and better urban construction.

MSW treatment pattern (TP) was the largest inhibitory factor, which decreased by 0.51 Mt CO_2e, with a contribution rate of −174.25%. TP changed from 94:2:4 in 2006 to 29:54:17 in 2019, namely the result of changing from a single sanitary landfill to a comprehensive treatment pattern based on incineration, supplemented by compost and sanitary landfill, causing the amount of MSW entering sanitary landfills to significantly decrease.

MSW treatment intensity (TI) was the second largest inhibitory factor, which decreased by 0.40 Mt CO_2e, with a contribution rate of −136.40%. TI declined significantly from 6.8 tons MSW/RMB 1,000,000 in 2006, to 2.9 tons MSW/RMB 1,000,000 in 2019, with a decrease of 57.35%, as the growth rate of MSW treatment amount is much smaller than GDP.

It can be seen that the contribution of TP, EO, EI and TI became larger, and the contribution of U and P became smaller, in phase 2011–2019 compared to phase 2006–2010.

3.3. Analysis of GHG Mitigation Potential of MSW Treatment

The GHG emissions of MSW treatment in different scenarios from 2020 to 2030 is shown in Figure 6. The GHG emissions in the BAU scenario decreased from 7.23 Mt CO_2e in 2020, to 6.71 Mt CO_2e in 2030, with an annual reduction rate of 0.74%. GHG emissions in the MSW classification scenario decreased from 7.09 Mt CO_2e in 2020, to 4.31 Mt CO_2e in 2030, with an annual reduction rate of 4.85%. GHG emissions in the population control scenario increased from 7.22 Mt CO_2e in 2020, to 6.68 Mt CO_2e in 2030, with an annual reduction rate of 0.78%. Compared with the BAU scenario, the emission mitigation potential by 2030 was about 35.79% for the MSW classification scenario, and about 0.51% for the population control scenario. It can be seen that the MSW classification scenario is an important means to reduce GHG emissions from MSW treatment, while population control scenarios do not contribute significantly to GHG emission mitigation.

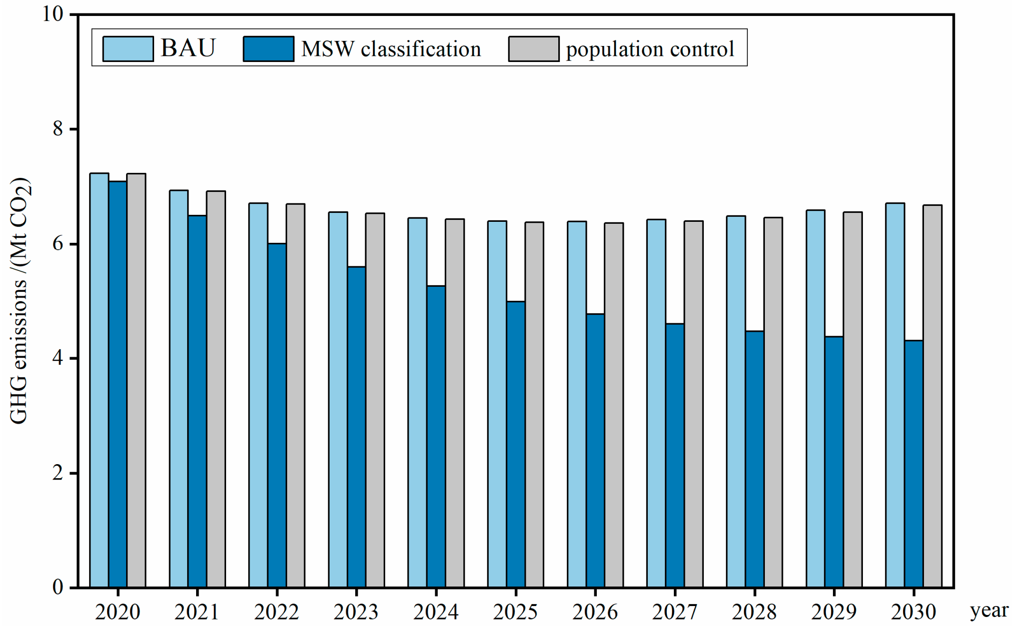

Figure 6. Comparison of GHG emissions from MSW treatment under different scenarios.

The share of GHG emission gas types from MSW treatment and the share of emissions from treatment facilities in the three scenarios are shown in Figure 7. In terms of the proportion of GHG, the proportion of CH_4 emissions decreased, and the proportion of CO_2 and N_2O emissions increased. CH_4 was the main GHG of MSW treatment, accounting for more than 70% during the period of 2020–2030 under three scenarios, and the proportion of methane in the MSW classification scenario was smaller than the other two scenarios. In terms of the proportion of GHG emissions from MSW treatment facilities, the share of GHG emissions from sanitary landfill decreased, and the share of GHG emissions from incineration and composting increased, under four scenarios. Sanitary landfill remains the main source of GHG emissions from MSW treatment during the period of 2020–2030, accounting for more than 40% under three scenarios. It can be seen that the percentage of GHG emissions from sanitary landfills was still as high as 42% when zero MSW is landfilled, under the MSW classification scenario.

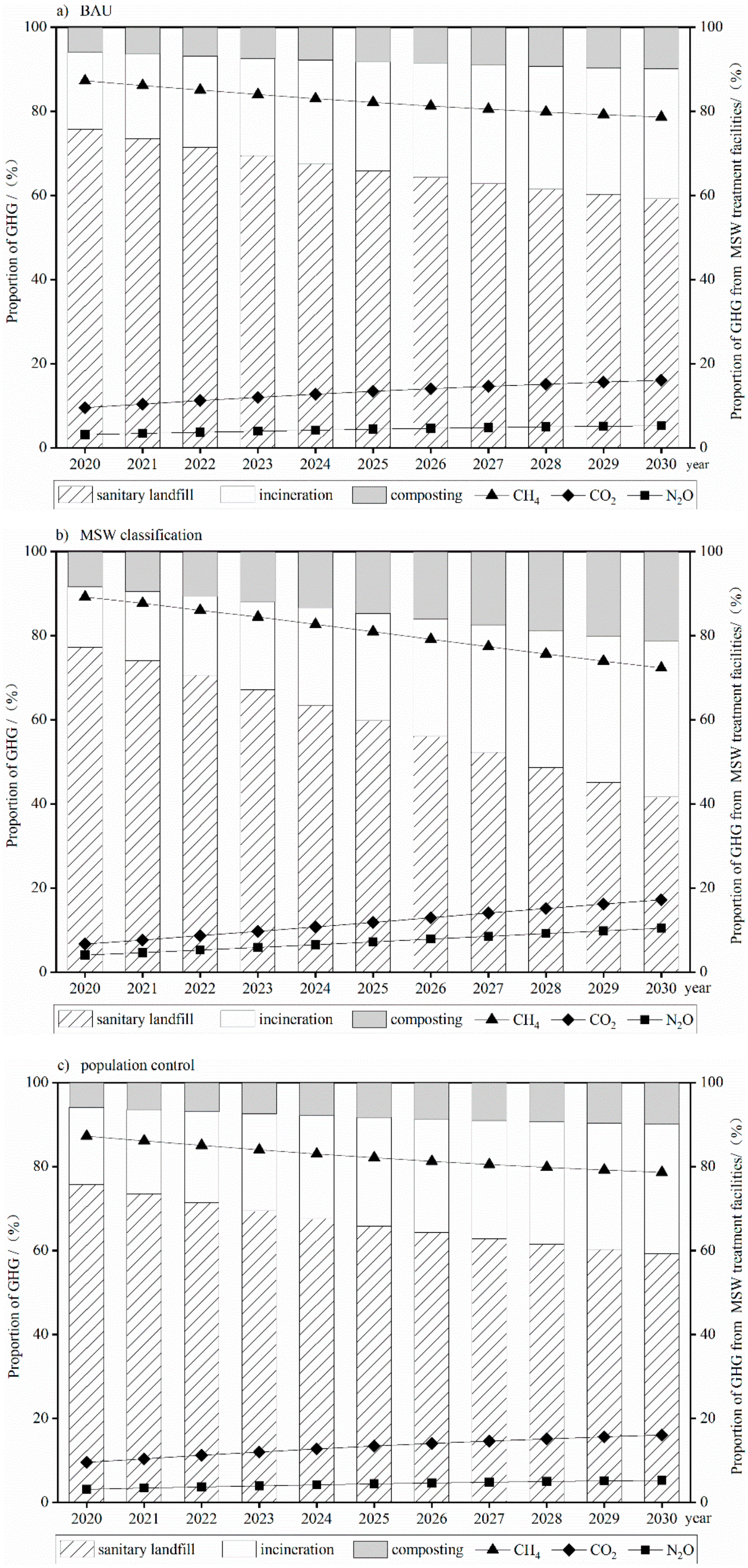

Figure 7. Share of GHG and GHG emissions from MSW treatment facilities under different scenarios ((**a**–**c**) is BAU, MSW classification, population control scenario, respectively).

4. Discussion

From the perspective of GHG emission intensity, the GHG emission intensity of sanitary landfill in this paper increased from 0.76 tCO_2e/t MSW in 2006 to 1.79 tCO_2e/t MSW in 2019, while Liu et al. [18], Yaman et al. [46], and Jeswani et al. [47] found Shanghai, Saudi Arabia, and UK, respectively, were 0.34–0.58 tCO_2e/t MSW, 0.27 tCO_2e/t MSW, and 0.40 tCO_2e/t MSW. The emission intensity calculated in this paper is larger when compared with the literature, which is mainly because this paper assumes Landfill 1991 as the base year with a long operating period, and China's mixed MSW landfilling has been characterized with high moisture content (40 to 60%) and perishable organic waste (50–70%) [48]. In this paper, the net GHG emission intensity of incineration treatment volume after incineration for power generation increased from 0.15 tCO_2e/t MSW in 2006 to 0.18 tCO_2e/t MSW in 2019, and 0.19 tCO_2e/t MSW for composting. Liu et al. [18] found 0.15–0.18 tCO_2e/t MSW for incineration for power generation and 0.19 tCO_2e/t MSW for composting in Shanghai. Yaman et al. [46] found 0.15 tCO_2e/t MSW for Dammam City in the Kingdom of Saudi Arabia, which is basically the same GHG emission intensity for incineration and composting treatment, compared with the literature.

In terms of influencing factors, this paper considers EO, EI, U, and P as the driving factors, while TI was the inhibiting factor of GHG emissions from MSW treatment, which is consistent with Xiao et al. [39], Kang et al. [49], and other related studies. It is worth noting that the EI effect had a slight driving influence on GHG emissions, indicating that the treatment technology has not been significantly improved. The improvement of MSW treatment technology may become an important measure to mitigate GHG emissions. In addition to this, the study found that the TP was an inhibiting factor of GHG emissions from MSW treatment, which is different from Xiao et al. [39] and Kang et al. [49]. This result is mainly due to Beijing's MSW treatment pattern commencing four years earlier than the national level to achieve the change from "landfill" to "incineration and composting"; the national MSW treatment pattern was 42:53:5 in 2019, while the MSW treatment pattern in Beijing was 36:44:20 in 2015.

In terms of GHG emission mitigation potential, this paper considered the potential of MSW classification policy and population control policy, and found that the emission mitigation potential of MSW classification and population control scenario would be, respectively, 35.79% and 0.51% by 2030, which is consistent with the study by Liu et al. [18], that the emission mitigation potential of a new policy (MSW classification, etc.) scenario would be about 54.07%. In addition, based on the above analysis of influencing factors, it was shown that the percentage of GHG emissions from sanitary landfills would still be as high as 42% when zero MSW is landfilled under the MSW classification scenario. MSW treatment technologies are also important pathways for GHG emission reduction, such as landfill treatment GHG emission reduction, by improving LFG collection and CH_4 oxidation efficiency [50,51]; and for incineration treatment, GHG emission reduction by MSW incineration technologies can also be combined with carbon capture and storage, but at a higher cost [24]. Moreover, promoting MSW reduction at source is an important way to reduce GHG emissions, such as advocating green production and lifestyle, promoting green packaging and packaging reduction, strictly enforcing the new "Plastic Restriction Order", and exploring innovative residential waste charging systems.

5. Conclusions

This paper presents a preliminary study on the GHG emission characteristics of MSW treatment in Beijing from 2006 to 2019, and a detailed decomposition and analysis of the factors affecting GHG emissions and mitigation potential. The results show that: (i) the GHG emissions from MSW treatment increased from 3.62 Mt CO_2e in 2006 to 6.57 Mt CO_2e in 2019, with an average annual growth rate of 4.68%; (ii) The main source of GHG emissions from MSW treatment was sanitary landfill, accounting for 79.61–98.56%, and CH_4 was the main GHG emitted from MSW treatment, accounting for 89.34–99.36%; (iii) The driving factors of GHG emissions from MSW treatment were, in descending order, economic output (EO), GHG emission intensity (EI), population size (P), and urbanization rate (U); and the inhibiting factors were, in descending order, MSW treatment pattern (TP) and MSW treatment intensity (TI); (iv) Compared with the BAU scenario, the GHG mitigation potential of the MSW classification scenario and population control is about 35.79% and 0.51% by 2030, respectively.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su14148398/s1, Table S1. GHG emissions from MSW treatment during the period 2006–2019 in Beijing. Table S2. GHG emissions from MSW treatment during the period 2020–2030 in BAU scenario. Table S3. GHG emissions from MSW treatment during the period 2020–2030 in MSW classification scenario. Table S4. GHG emissions from MSW treatment during the period 2020–2030 in population control scenario

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Appendix A

Table A1 shows the statistical values of MSW generation, population size, GDP, and treatment capacity of various facilities (sanitary landfill, incineration, and composting) in Beijing from 2006 to 2019, and Table A2 shows the physical composition of MSW in Beijing from 2006 to 2019.

Table A1. The contribution value of each decomposition factor of MSW treatment GHG emissions in Beijing from 2006 to 2019.

Year	P	UP	GDP	G	$G_{\text{sanitary landfill}}$	$G_{\text{incineration}}$	$G_{\text{composting}}$
2006	1601	1333	8117.8	497.7	468.3	9.8	19.6
2007	1676	1380	9846.8	575.3	535.1	1.0	39.1
2008	1771	1439	11,115.0	641.6	598.8	15.7	27.0
2009	1860	1492	12,153.0	644.4	548.1	68.7	27.6
2010	1962	1686	14,113.6	613.7	445.4	89.1	79.3
2011	2019	1740	16,251.9	623.2	429.6	94.5	99.2
2012	2069	1784	17,879.4	633.1	443.2	94.7	95.3
2013	2115	1825	19,800.8	667.0	489.9	97.8	79.2
2014	2152	1858	21,330.8	730.8	488.6	156.1	86.2
2015	2171	1878	23,014.6	622.4	325.8	209.4	87.3
2016	2173	1880	25,669.1	872.6	472.8	272.5	126.0
2017	2171	1878	28,014.9	924.8	438.0	326.5	159.2
2018	2154	1863	30,320.0	975.7	393.8	399.7	181.6
2019	2154	1865	35,371.3	1011.2	292.0	548.9	170.0

Table A2. Statistical table of physical components of MSW in Beijing from 2006 to 2019 (%) (Adapted with permission from Refs. [24,44–46]).

Year	Food	Paper	Plastic	Textile	Wood	Total Moisture Content
2006	63.40	11.10	12.70	2.50	1.80	-
2007	66.20	10.70	12.30	1.60	2.30	-
2008	66.20	10.90	13.10	1.20	3.30	62.9
2009	63.20	12.60	15.30	1.20	3.20	62.14
2010	66.00	11.00	12.30	1.50	3.80	62.93
2011	58.96	15.87	16.78	1.34	2.50	61.58
2012	53.96	17.64	18.67	1.55	3.08	59.16
2013	54.58	18.40	18.20	1.15	2.78	59.07
2014	53.89	17.67	18.70	1.05	3.08	59.18
2015	53.22	19.60	19.59	0.72	2.83	58.74
2016	56.84	18.33	18.77	1.00	0.61	58.3
2017	53.96	17.64	18.67	1.55	3.08	57.86
2018	50.65	20.98	21.62	0.47	3.53	58.18
2019	49.85	22.17	21.45	0.98	3.43	-

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