The Waste Management System in China and Greenhouse Gas Emission Inventories

Lou Ziyang, Xing Zhilin, Cheng Zhaowen, Zhao Tiantao, and Cai Bofeng

Abstract The increase in waste generation amounts and its Greenhouse gas (GHG) emissions are two main pressures for the Chinese government. The development process of the waste management system was summarized. The corresponding GHG emissions pattern was studied, and the potential reduction measurements were also proposed based on the different steps for the waste management system. It was found that the total estimated GHG increased from 10.95 million tons (1991) to 72.4 million tons CO_2-equiv (2013) on the basis of the IPCC methods. Landfill was the main GHG source, as the corresponding percentage increased to the peak of 82% (1999) and finally to 69.5% (2013) in the period studied. Eastern China was the dominant CO_2 emission region, while the percentage decreased from 39.6% (2003) to 26.4% (2013). To get more detailed GHG emissions from landfills, the bottom-to-top method was applied to estimate the corresponding emissions and reduction potential from 1,955 landfills in 2012. The source reduction in MSW and the diversion alternatives for landfills are indirect, while useful GHG mitigation way for the reduction of the terminal disposal amounts and its GHG emissions through the implementation of "pay-as-you-throw" and an environmental protection tax.

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Contents

Abbreviations

EC	Eastern China
FOD	First-order decay model
IPCC	Intergovernmental panel on climate change
LCF	Landfill gas collection and flaring
LCSR	Landfill cover soil reactor
LFG	Landfill gas
MC	Middle China
MHDC	Ministry of Housing and Urban-Rural Development of the People's Republic of China
ML	Mineral landfill
MSW	Municipal solid waste
Mt	Million tons
NC	Northern China
NE	Northeastern China
NMS	Nitrate mineral salts
NW	Northwestern China
OLCS	Original landfill cover soil
PVC	Polyvinyl chloride
RL	Renewable landfill
RPL	Refinement process for MSW landfilling
SC	Southern China
SLCS	Simulated landfill cover soil
SW	Southwestern China

1 The Waste Sector in China

With the rapid development and the urbanization process, waste generation has increased greatly. The waste generation rate relies greatly on the population, its living habits/levels, and the urbanization process. China, as the most populous (22% of the global population) and fastest growing emerging country in the world, consequently increased its annual municipal solid waste (MSW) generated from 245 kg per capita in 1991 to 275 kg per capita in 2013, and almost ten times the annual MSW of 178.6 million tons was produced in 2014 [1]. The basic waste information in China in 2014 is shown below (Table 1):

It could obviously be observed that around 0.179 billion tons of MSW was collected, and 91.7% has been disposed in a sanitary way, among which 65.4% of total MSW was disposed in a sanitary landfill, and 32.4% was incinerated. The rest was disposed in other ways, such as composting or resource and recycling. However, the waste management system was not well recorded before 1978, when the ministry of housing and urban-rural development of the People's Republic of China (PRC) started to work on for the urban waste system. The official MSW data, including MSW collection and disposal amounts, was compiled and inventoried annually in the China Urban Construction Statistical Yearbook, although the statistical data was not consistent, and inconsistent data in some years was found due to the different statistical caliber and sampling representative. Landfills (including open dumping sites), incineration, and composting have been the three main disposal processes in the past few decades, among which incineration increased very quickly from 47 plants in 2003 to 187 plants in 2014, with almost 100 plants under construction, while composting has been greatly reduced because of the lack of acceptable routes for composting products [1]. Despite many efforts to reduce MSW landfilling and control large landfill emissions, the landfill sector remains the predominant MSW disposal process because of the increasing waste streams in China, which increased from 64.04 million tons of waste from landfilling in 2003 to 107.28 million tons in 2014, according to the statistics data [1]. Even for the megacity of Shanghai, MSW landfilling, including the dumping sites, is still predominant in the whole waste disposal process, with an occupied percentage

Table 1 MSW disposal information in 2014 in China [1]

Collected and transported (10,000 tons)	Number of harmless treatment plants/grounds (units)	Sanitary landfill	Incineration	Other
17,869.09	819	605	187	26
Volume of treated (10,000 tons)	Harmless treatment capacity (tons/day)	Sanitary landfill	Incineration	Other
17,226.68	532,825	334,986	185,157	12,182
Volume of harmlessly treated (10,000 tons)	Sanitary landfill	Incineration	Other	
16,398.62	10,728.21	5,332.99	319.59	

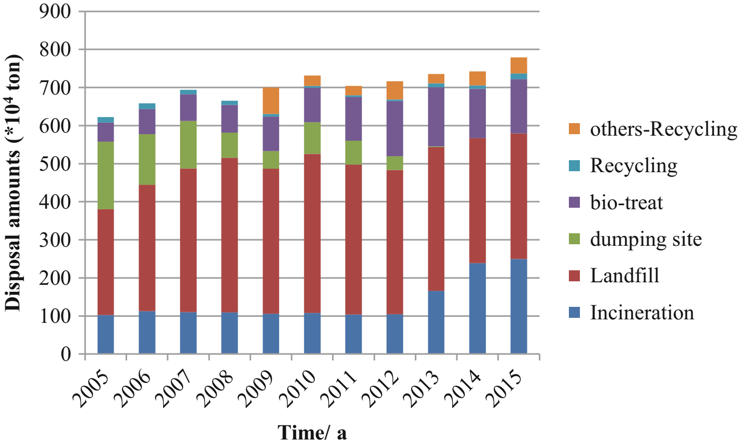

Fig. 1 Basic disposal information for Shanghai over the past 10 years

range of 41.6–73.2%, although MSW incineration has increased quickly over the past 5 years (Fig. 1).

2 GHG Emissions from Waste Sectors

China faces an increasingly complex set of environmental and social pressures for MSW reduction and CO_2 mitigation, especially after joining the Paris Agreement in 2015. Economic growth is the major underlying cause for GHG from diverse human activities, and the waste sector is the main part, since it links our industrial and life activities greatly. Currently, the ever-increasing amount of waste is one of the urgent challenges for modern cities to an extent that most of them have been christened as “cities besieged by garbage.” In fact, the waste industry is considered as one of the significant sources of anthropogenic GHG, a matter that is currently of great concern to environmentalists. It has been estimated that the waste sector was the third largest contributor to global emissions of non-CO_2 greenhouse gasses, accounting for 13% of total emissions [2]. MSW properties in China are totally different from those in developed countries, which are characterized as “three high and one low,” i.e., high mixture, high inorganic matter content, high percentage of putrescible waste (more than 55% with consequent high moisture), and low calorific heating value [3], since a non-classified waste management system is applied as a waste collection system. Therefore, more CH_4 was released from landfills. The comprehensive and accurate estimation of GHG becomes increasingly important step for the achievement of the GHG reduction target.

The activity data for individual waste treatment facilities were based on the national waste treatment facilities' sanitary level assessment projects led by the Ministry of Housing and Urban-Rural Development, carried out in China in 2006, 2009, and 2012 [4, 5]. Emissions factors, such as the critical factor of R, were chosen based on the national landfill assessment results of 2006, 2009, and 2012, and $t_{1/2}$ was set according to our lab experiments and waste composition [6–8]. The first-order decay (FOD) model recommended by Intergovernmental Panel on Climate Change (IPCC) guidelines has been applied for GHG emission from landfills.

Waste composition and the relative key parameters were the critical factors for the GHG emissions calculation, and the operation parameters, such as correction factor, CH_4 content, CH_4 recovery rate and oxidation factor in landfills, burning efficiency in incineration plants, and CH_4 and N_2O generation rate in composting, were the combined results from the field investigation, laboratory analysis, literature review, and the experts' judgment. GHG emissions were calculated by multiplying the MSW disposal in different facilities with its respective emissions factors in IPCC methods. The total GHG emissions from the waste sector were aggregated based on the individual values from each treatment process and finally normalized into CO_2-equiv value.

$$\mathrm{CO}_{2\,\text{landfill}} = \mathrm{CO}_{2\,\text{sanitary landfill}} + \mathrm{CO}_{2\,\text{open dumping sites}}$$

$$\mathrm{CO}_{2\,\text{incineration plant}} = \mathrm{CO}_{2\,\text{incineration plant}} + \mathrm{CO}_{2\,\text{open burning}}$$

$$\text{Total GHG emission} = \mathrm{CO}_{2\,\text{landfill}} + \mathrm{CO}_{2\,\text{incineration plant}} + \mathrm{CO}_{2\,\text{composting}}$$

3 China's Contribution for GHG Emissions from Waste Sector

3.1 GHG Pattern from the Waste Sector

The GHG emissions from the MSW sector in China from 1991 to 2013 are represented in Fig. 2.

The CO_2 emissions from the MSW sector gradually increased from 10.95 million tons (1991) to 72.40 million tons (2013) over the last decade. The CO_2 emission patterns vividly indicated that China experienced tremendous MSW generation growth after 1991 with the expanding of the MSW collection area and more and more large-scale modern treatment facilities becoming operational. Based on the bottom-up methods, total CH_4 emissions of 1.48 million tons were estimated from 1955 landfills in 2012, 24.88% higher than that those in 2007 [6]. It could be inferred that landfills were the main contributors. A small number of sanitary landfill sites were either under construction or operational, but at the same time, the amounts of large-scale unsanitary or semi-sanitary landfills sites increased from less than twenty (1990) to thousands in number (in 2000), and the burgeoning

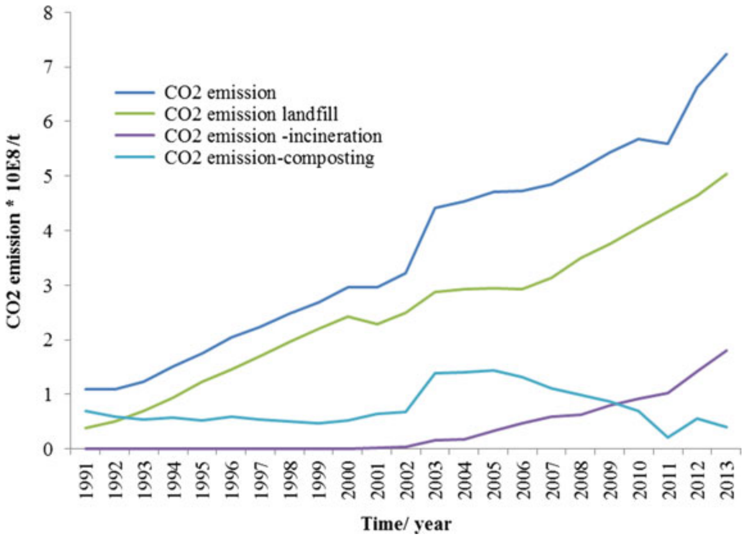

Fig. 2 Variations in CO_2 emissions from the MSW sector in China from 1991 to 2013

unsanitary landfills caused rapid growth in CO_2 emissions. It is a delight to find that the unsanitary landfills were supposed to be closed, and modern large-scale sanitary landfills were promoted after 2003. It can be found that only 143.4 kg of CO_2 emissions per ton of waste disposal were released in 1991, while it increased to 297.2 kg in 2003 and 420 kg in 2013. This discrepancy owes to the fact that old MSW accumulated in a landfill contributes to a large amount of CO_2 emissions, which resulted in the higher CO_2 emissions in the later period of observation time. Compared to the CO_2 emissions from the MSW sector, the incremental tendency of the waste generation rate was found to be a little slow, from 0.245 tons annually/cap. in 1991, 0.284 tons annually/cap. in 2003, and then decreasing to 0.236 tons annually/cap. in 2013. The increase in the urban population, rapid urbanization process in the western region, and the different statistical caliber might result in the decrease in the national MSW generation rate after 2006 [9].

3.2 Regional Distribution of the GHG Pattern

The temporary and spatial distribution of CO_2 emissions from the MSW sector in seven regions are shown in Fig. 3.

It was observed that total CO_2 emissions from MSW sectors showed an increasing trend in past decades, especially in the period from 2003 to 2008, because of the rapid construction and operation of MSW treatment facilities and the regional disparity patterns that were also observed. A notable increment of total CO_2 emissions was observed in the EC, SC, and SW regions, and around 1.2–1.7

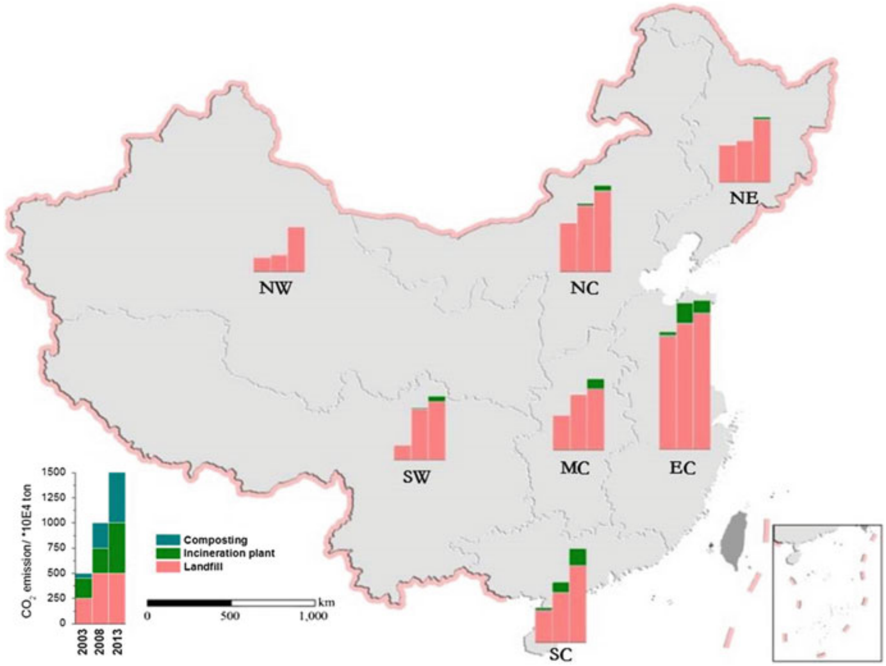

Fig. 3 Total amounts and individual CO_2 emissions from waste sectors in seven regions. The first, second, and third columns from the left to right show the GHG emissions released in 2003, 2008, and 2013, respectively. The columns consist of three sub-columns with different colors, which signify the GHG emissions from landfills (*pink*), incineration plants (*green*), and compositing (*blue*). Note: *NC* North China, *NE* North East, *EC* East China, *MC* Middle China, *SC* South China, *SW* South West, *NW* North West

times and 1.6–2.7 times higher CO_2 emissions in 2008 and 2013 were reported, respectively. A sharp increase of 3.4 times and 4.2 times higher CO_2 emissions was observed in the SW in 2008 and 2013, followed by NW, with 3.15 times higher each, compared to the base year of 2003. The possible reason was a dearth of MSW disposal treatment facilities in the NW and SW before 2003, and more and more waste disposal facilities put into operation. As a consequence of that, there was a sharp increase in CO_2 emissions, since the non-hazardous waste disposal rate of over 80% was the basic requirement for the local government to apply to the state level as a healthy city. The SW region had a maximum increase in the waste disposal rate, at 3.4 times higher than that of 2003, followed by the SC and MC regions, with 1.73 and 1.60 times higher each. A rapid rise in CO_2 emissions occurred between 2008 and 2013 in the NW, at 3.15 times higher compared to that in 2003.

EC contributed almost one-third of national CO_2 emissions from the waste sector in the last 10 years due to its high population density and living standard and had peak CO_2 emissions of 23.68, 29.58, and 33.20 million tons of CO_2 in years

2003, 2008, and 2013, respectively. However, the occupied percentage decreased from 38.6% (2003) to 30.7% (2013), because CO_2 emissions from other regions experienced a dramatic increase in the same period, with more MSW disposal facilities operated, such as landfills.

The highest CO_2 emissions from landfills were recorded in 2003 at 96.8%, then onward, a decreasing trend of 91.8% was observed in 2008, and in 2013, it reached 84.7%. More incineration plants came into existence after 2002. For the GHG emissions from landfills in individual regions, it decreased sharply in the EC from 96.1% to 71.9% and in the SC and MC declined from 91.7% to 81.8% and 98.9% to 85.7% from 2003 to 2013, respectively. Generally, a high economic level and limited land for landfill sites were the main causes of these changes, since the construction and operational investments in incineration plants were normally two times higher than that of a landfill. CO_2 ranked as the largest pollutant emitted with 10.687 million tons in 2013, and around 46% of total MSW collection was incinerated in the EC. The percentage of incineration plants increased from 3% (2003) to 14% (2008) and finally reached 28% (2013). It was noticed that only 28% of GHG emissions were from incineration plants in the EC, indicating that less GHG emissions per ton of waste disposal were released from incineration plants. For CO_2 emissions from composting plants, the maximum of 1.0% CO_2 emissions was recorded in 2003 in the MC region, which further decreased to 0% in 2013 due to discontinuing the operation of the composting plants. Therefore, landfill and incineration were the two main sources for the CO_2 emissions. The increase in disparity trends was observed between the period of 2003–2008 and 2008–2013 in these different regions. It was observed that the CO_2 emissions per capita varied in 2003 from the different regions, while the disparity in 2013 decreased. With these results, it could be inferred that many treatment facilities in operation applied some efficient mitigation methods in the past 10 years, such as landfill gas collection and utilization, CO_2 capture from the flue gas in the incineration plant, and high efficient aeration facilities used in composting.

Since landfills are the main contributors of GHG emissions from waste sectors, the spatial distribution of CH_4 emissions from landfills in 2012 is shown in Fig. 4. Total CH_4 emissions reached 1.48 million tons in 2012, 24.88% higher than in 2007 [6]. Eastern China, southern China, and northern China are the first three main contributors, with annual CH_4 emissions of 48.89, 21.90, and 18.38×10^4 tons of CH_4, which comprised around 33.00, 14.79, and 12.41% of total CH_4 emissions from landfills in series. The maximum CH_4 emissions were found in eastern China, with the highest GDP value of 2087.81 billion RMB in 2012. The lowest GDP value of 318.44 billion RMB was found in northwestern China, and the lowest CH_4 emissions of 12.97×10^4 ton were released. Population will influence the CH_4 generation rate, while the different tendency was observed in these seven regions. More CH_4 emissions were found in southern China and northeastern China, meaning that CH_4 emissions rely more on the economic level and living habits, instead of the population.

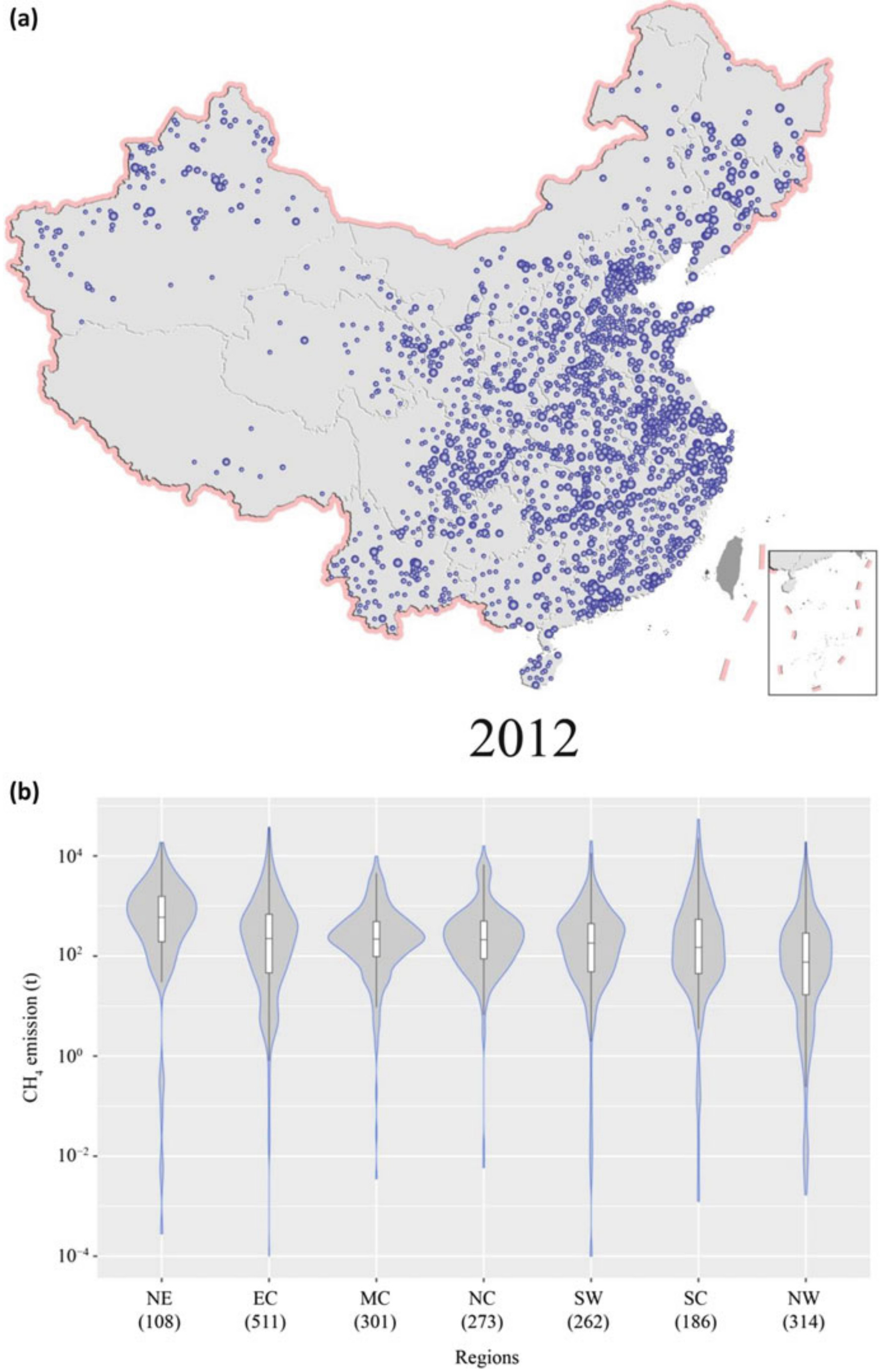

Fig. 4 The CH_4 emission pattern from landfills in 2012. (**a**) The detailed CH_4 emissions; (**b**) The distribution of CH_4 emissions in seven regions

From Fig. 4b, we can see that CH_4 generation amounts rely on the landfill scales greatly, and some large-scale landfills produced more than 10,000 tons of CH_4 per year, while some small-scale landfills might produce less than 10 tons. In 2012, around 45.88% of CH_4 was generated from level I landfills, and 25.77 and 28.35% of CH_4 were released from level II and III landfills, respectively. Different generation patterns were observed in seven regions. The mean values of the CH_4 generation amounts from landfills in all regions, except in the NW, were above 100 tons, and landfills in the NE have the maximum mean value of 594 tons, where more than 75% of landfills produced more than 100 tons of CH_4 annually in the NE. For the MC and NC, half of the landfills generated CH_4 in the range of 100–1,000 tons, meaning that these landfills were of similar scales and operational conditions. The maximum CH_4 emissions from landfills were found in the SC and EC regions, where some landfills generated more than 10,000 tons of CH_4. A varied dispersion of CH_4 emissions was observed in landfills in the SW and NW regions, since the landfill scales in these two regions were more heterogeneous.

Most CH_4 was released from level I landfills in the EC, SC, and NC, with 53.5, 66.4, and 44.0% of total CH_4 emissions, meaning that most of landfills in these areas are large-scale landfills due to the heavy pressure from MSW disposal requirements, and CH_4 utilization or mitigation measurements could be conveniently applied. The core CH_4 emissions area concentrated in the areas of Beijing Tianjin, Shanghai-Shaoxing-Ningbo, and Guangdong-Dongguan-Qingyuan, which is the developed area in China with the mature urbanization process. For the other areas, CH_4 emissions were mostly from the level II and III landfills, especially for the SW, MC, and NW, where around 41.5, 34.0, and 31.0% of CH_4 are released from level III landfills, suggesting that more low-tech CH_4 control methods, such as biocovers, might be the suitable CH_4 control option. Meanwhile, there were more small-scale landfills in these two regions, and around 25% of landfills released less than 10^{-4} tons of CH_4 annually.

4 GHG Abatement Measures from Waste Sector

GHG abatement measures should be considered and applied in the waste sector, and mitigation technologies and diversion alternatives were two promising methods [2], which the former could be used to capture and destroy the GHG generated from landfills and other facilities and the later could be used to reduce the waste generation rate at the source.

4.1 Policy Analysis

GHG emissions from landfills rely greatly on the waste disposal amounts, and the source reduction of MSW is the basic principle through reduction, recycling, and reuse. China has introduced a series of policies to facilitate MSW management.

A long-term strategy for diverting MSW away from landfills and increasing recycling should be created and implemented in China [2], and the government's respond for the constitution of the long tradition for developing waste strategies and plan on the national level. The requirement of MSW pretreatment before landfilling combined with other management activities, such as producer responsibility [10], have been proven to be the strong drivers in diverting MSW away from landfills and toward recycling, which would be useful for the reduction of organic matter landfilling and CH_4 emissions from landfills. The increase in R&D investment should be implemented and stimulated to improve the mitigation technologies and diversion alternatives in the waste sector in China [11].

From the Chinese government side, the Ministry of Housing and Urban-Rural Development of China should try to include the polluter pays principle (PPP) in the waste management system and the new Municipal Solid Waste Management Rule that was released on April 10, 2007, which emphasized the principle of "the person who produces the waste has a responsibility to its corresponding disposal." Many developing countries have extended the PPP to show the obligation of the state for compensating the victims of environmental pollution. In China, the government makes the most dominant contribution to MSW disposal. Moreover, the MSW disposal fee is supposed to be charged according to the cost of MSW disposal and the income level of citizens, often known as the quota system. However, the quota system seems to have a limited contribution to MSW reduction. This phenomenon can be attributed to the fact that the fee charged for MSW disposal is not directly influenced by the volume of MSW it produces. In Europe, effective economic incentives are provided to encourage residents to reduce and recycle MSW. Specially, pay-as-you-throw (PAYT) schemes are a variable pricing mechanism from municipalities in which households are charged according to the quantity of non-recyclable waste they generate and corresponding services of MSW disposal they receive. Considering that PAYT schemes are a cost-effective way to manage MSW and stimulate recycling, this measure has already been widely conducted in Europe, Japan, and the USA. Reports have also shown that countries making effective economic incentives have better performance on MSW recycling and reduction. Notably, proper MSW classification is the premise for achieving the effective management of MSW due to its significant contribution to resource recycling. Previous research has indicated that the level of public awareness has a significant influence on the effectiveness of MSW management. Hussain et al. [12] suggest that residents should be educated in schools and colleges to improve their public awareness toward the proper classification and reduction of MSW. Therefore, effective economic incentives and environmental education to improve public awareness toward MSW classification and reduction at the household level are highly suggested to improve GHG reduction potential.

The "Opinions on Further Strengthening the work of MSW disposal" was approved by the State Council of China on April 19, 2011. This report emphasizes that the resource utilization of MSW (including MSW for energy and recycling) should be further developed. MSW for energy includes energy recovery from the direct combustion of MSW (e.g., incineration, pyrolysis, and gasification) and the production of combustible fuels (e.g., methane and hydrogen). This process can both reduce methane emissions generated from landfills and avoid the CO_2 emissions generated from coal-based electricity generation, which will mitigate global warming from a long-term perspective. It's obvious that the alternative of MSW-based energy will make a significant contribution to mitigate the serious problem of fossil fuel (e.g., coal) depletion, which currently afflicts the rapid development of China [13]. As part of the Kyoto Protocol's response toward the mitigation of global warming, the Clean Development Mechanism (CDM) has developed rapidly in recent years. One of its dominant objectives is to achieve sustainable development in developing countries by providing funds, advanced technologies, and equipment from developed countries. Especially, most of the CDM projects approved by the National Development and Reform Commission (NDRC) are renewable energy projects. Therefore, the implementation of MSW for CDM energy projects and CCS technologies in these plants is also highly recommended.

4.2 GHG Mitigation Process for Incineration Plants

The separation of a highly calorific light fraction to be used for waste incineration can be achieved by rotating trommel screens with screen sizes of 40 and 80 mm, and over 92% of MSW could be separated from unclassified MSW. Three fractions with a different size range and waste composition, namely, >80, >40, and <40 mm, could be obtained, as shown in Table 2. Only 24.75% of the total MSW is found in the fraction with a mesh size of >80 mm, and the fraction with the mesh size of >40 mm occupies around 45.25% of the total MSW. The fraction to 40 mm of screen underflow is supposed to be landfilled. The application of the >40 mm fraction might be one of the feasibility methods for the sorting operation from an economic and practice perspective thereafter. Some inner materials, i.e., glass and metals, could also be removed simultaneously, with the percentage of 11.59%. The residues of <40 mm will be about 43.2%, and over 80% of the biodegradable fraction was found to be 40 mm screen underflow, while the percentage of organic matter decreased from 70.60 to 45.49% after MSW sorting out the 40 mm screen overflow, and the percentage of main high calorific value contributors (like plastic and paper) increased from 12.8% to 25.84% and 7.3% to 13.78%, respectively. The estimated heating values in raw waste, >40 mm fraction and >80 mm fraction, are 3935.0, 5810.7, and 7283.8 kJ/kg, respectively, and thus the introduction of the larger size fraction might get better combustion performance in the incineration plant.

The environmental impacts before (all MSW was treated by incinerating) and after sorting (MSW of the 40 mm screen overflow was treated by incinerating and that of the 40 mm screen underflow was landfilled) are compared. The GW100 impact from the waste treatment process turned from the impact to the benefit, as the size of the waste decreased from >40 mm to the raw MSW, with the value of −0.0007 PE and 0.002 PE per ton MSW, respectively. CH_4, CO_2, and CO are the

Table 2 The distribution of waste composition in different size ranges (%)

Composition	>80 mm	40–80 mm	>40 mm	Raw MSW
The percentage	24.75%	20.05%	45.25%	100
OM	27.51	63.06	44.07	70.60
Plastic	34.90	15.97	25.84	12.80
Paper	12.55	15.36	13.78	7.30
Textiles	9.21	4.85	6.43	3.20
Resident	6.32	3.14	4.28	2.40
Wood	0.30	0.19	0.23	0.10
Metals	4.61	0.15	2.50	0.30
Rubber	0.00	0.02	0.01	0.20
Soil	0.00	0.45	0.17	0.10
Glass	4.61	0.63	2.71	3.00

Table 3 The classification process of the waste sector

Phases		Implementation
Pilot project	1995	Establish pilot of garbage classification in No. 5 Caoyang village
	1998	Special recycling of used batteries and used glass
Promotion stage	1999	Garbage classification incorporated into environmental plan
		Issue files of living waste classification collection and disposal
	2000	Establish pilots of garbage classification in 100 residential areas
		One of the eight pilot cities of garbage classification in China
	2002	Focus on promoting the work of classification in incineration area
	2006	Coverage ratio of garbage classification is more than 60% in urban areas
	2007	Promoting the new style: four categories, five categories
	2009	Coverage ratio of garbage classification is 100% around Expo park
	2010	Coverage ratio of garbage classification is more than 70% in urban areas
Adjustment stage	2011	Overfulfilled pilots of classification in 1,009 residential areas
		Realize target of 5% reduction rate per capita in 2010, 0.76 kg/day
	2012	Establish 3,271 new pilot sites
		Realize target of 5% reduction rate of per capita in 2010, 0.74 kg/day
	2013	Increased classification pilot: 2016, coverage area: 8×10^5households
		Realize target of 5% reduction rate per capita in 2010, 0.7 kg/day
	2014	Classification pilot: 11,000, coverage area: 2.8×10^6 households
		Realize target of 5% reduction rate per capita in 2010, 0.66 kg/day

main contributors, with values of 57.28, 24.21, and 0.34 CO_2-eq, since some biocarbon in landfills is converted as CH_4, while that in incineration plant will be as CO_2, which will not be considered as the source for GW impact [3].

On the other hand, the source separation program has been encouraged and implemented in Shanghai to reduce the amount of MSW generation. The history of the classification program in Shanghai was summarized in Table 3.

With the implementation of source separation, we can conclude that the waste disposal amounts and the relative GHG emissions could be reduced significantly. Usually, the GHG emission from incineration plant will be lower than that from landfill per MSW disposal, even so, CO_2 capture and storage could be the promising mitigation methods for the incineration plant based on the high content of 8–12% CO_2 content in flue gas [3].

4.3 Mitigation Technologies for Landfills

Once the MSW was disposed of, especially in landfills, the typical GHG mitigation processes, such as soil cover, landfill gas (LFG) collection and flaring, LFG collection and electricity production, and LFG collection and purified/utilization, could be applied for CH_4 mitigation [2, 6]. The mitigation technologies should be implemented according to the local conditions. A major control of CH_4 emissions can be done by limiting the amount of organic matter at the source through the introduction of RL and MBT processes. For the western inland regions, CH_4 mitigation processes such as LCF, FSC, and LCP should be the first choice, whereas in the eastern coastal regions, the waste diversion options are the most promising measures.

Landfill gas collection/flaring and CH_4 oxidation through soil cover have been proven to be cost-effective and practical mitigation measurements [2, 14]. For the former one, it has been widely applied in many large- and middle-scale landfills with the incentives of CDM projects, especially the power generation from biogas. On-site methane reduction is the most cost-effective measure for the reduction of CH_4 emissions, and the detailed introduction is shown in part 5 of case study.

5 Case Study: CH_4 Mitigation Through the Improvement of Methanotrophs in Landfill Cover

Landfill soil cover is the forced construction part of a modern sanitary landfill, and it has been proven to be one of the cost-effective CH_4 mitigation technologies that could be applied to all of the landfills. As early as 1970, Whittenbury found that methanotrophs *Methylocystis sporium*, *Methylocystis methanica*, and *Methylocystis albus* showed enhanced growth on methane when malate, acetate, or succinate was also present in the culture medium, and these findings suggested that facultative methanotrophs may exist [15, 16]. Efforts to identify novel methanotrophs didn't significantly regain momentum until the discovery of the *Methylocella palustris* [17], which was a new genus and species within *Alphaproteobacteria* in 1998. After that, *Methylocella silvestris* and *Methylocella tundrae* [18–20] were isolated. These methanotrophs were later shown to be facultative, as they could utilize not only one

Table 4 Facultative methanotrophs

Strains	Discoverer	Discovery time	Discovery area	Metabolic characteristics
Gram-negative, strictly aerobic methane-utilizing bacteria	[23]	In 1970	–	A wide variety of methanotrophs, *sporium, methanica*, and *albus* experienced enhanced growth from methane when malate, acetate, or succinate was also present in the culture medium
Methylobacterium organophilum	[24]	In 1974–1976	Freshwater lake sediments and water	These could utilize a wide range of multicarbon compounds as growth substrates, including many organic acids and sugars. This strain, however, lost the ability to oxidize methane when grown repeatedly on glucose, and other workers subsequently did not succeed in growing the strain on methane [15, 16]
Methylobacterium ethanolicum strain R6	[25–27]	In 1978	An oil refinery in the northeastern United States	These strains were able to grow solely on glucose, but not with other sugars such as fructose, galactose, or sucrose
Methylobacterium ethanolicum	[24, 28]	In 1980	Freshwater lake sediments	They were able to utilize not only methane but also casamino acids, nutrient agar, and a variety of organic acids and sugars for carbon and energy
Methylobacterium hypolimneticum				
Methylomonas sp. strain 761M/ 761H	[26]	In 1984	A rice paddy in South China	Only 761M could grow on methane, but 761H could not grow on glucose as the sole carbon source, and glucose, as well as acetate and malate, was reported to enhance its growth on methane

(continued)

Table 4 (continued)

Strains	Discoverer	Discovery time	Discovery area	Metabolic characteristics
Methylocella palustris	[17]	In 1998	*Sphagnum* peat bogs	It was the first characterized acidophilic methanotroph which brought significantly regained momentum to identify novel methanotrophs
Methylocella silvestris BL2	[19]	In 2003	Cambisol under a beech-dominated forest stand near Marburg, Germany	These methanotrophs, however, were later shown to be facultative, as they could utilize not only C1compounds for growth but also acetate, pyruvate, succinate, malate and ethanol
Methylocella tundrae	[29]	In 2004	Acidic *Sphagnum* tundra peatlands	
Methylocapsa aurea	[21]	In 2010	A soil sample collected in March 2003 from under a small ephemeral brook in a forest near Marburg, Germany	It was identified that they could utilize acetate as the sole growth substrate; however, *M. aurea* only expresses pMMO
Methylocystis strain H2s/*heyeri* H2	[22]	In 2011	A sample collected in July 2001 from 10 cm below the surface of *Sphagnum* peat	It possesses both forms of methane monooxygenase (particulate and soluble MMO) and a well-developed system of intracytoplasmic membranes (ICM) and is able to grow with the acetate absence of methane
Methylocystis strain SB2	[22]	In 2011	A spring bog in southeastern Michigan	It was able to utilize methane, ethanol, or acetate as growth and can only express pMMO substrates

(continued)

Table 4 (continued)

Strains	Discoverer	Discovery time	Discovery area	Metabolic characteristics
Methylocystis strain H2sT *Methylocystis* strain S284	[30]	In 2012	An acidic (pH 4.3) *Sphagnum* peat bog lake (Teufelssee, Germany) and an acidic (pH 3.8) peat bog (European north Russia)	They possess both a soluble and a particulate methane monooxygenase. The preferred growth substrates are methane and methanol. In the absence of C1 substrates, however, these methanotrophs a22re capable of slow growth on acetate

carbon compound for growth but also acetate, pyruvate, succinate, malate, and ethanol.

Shortly thereafter, *Methylocapsa* [21] and *Methylocystis* [22] were also isolated and suggested to be facultative methanotrophs. In contrast to *M. silvestris*, the newly acidophilic methanotroph, *Methylocapsa aurea*, only expresses pMMO and has well-developed intracytoplasmic membrane (ICM) systems. Additionally, *M. aurea* grew best on methane, with a maximum $OD_{600} = 1.2$ $\mu_{max} = 0.018\ h^{-1}$. The discovery process of facultative methanotrophs is shown in Table 4.

According to the reported of facultative methanotrophs, *Methylocella silvestris* (BL2) was capable of growth at pH values between 4.5 and 7 (with an optimum at pH 5.5) [19], *Methylocella tundrae* was capable of growth between pH 4.2 and 7.5 (optimum 5.5–6.0) [29], *Methylocapsa aurea* KYG^T grew at pH 5.2–7.2, and *Methylocystis* H2s was mesophilic with optimum pH 6.0–6.5. The optimum pH of *Methylocystis heyeri* H2 [21] and *Methylocystis* SB2 [31] were 5.8–6.2 and 6.8, respectively. *Methylocystis* strain H2sT and S284 grew at pH 5.2–7.2 and 6.0–6.5 [30]. These results indicated that facultative methanotrophs grew well in acidic conditions, and the optimum pH was 5.5–6.5, as shown in Fig. 5.

The relationship between CH_4 oxidation and CH_4 concentration (10–60%) was shown in Fig. 6. It was obvious that there was a positive correlation between the CH_4 oxidation rate and the concentration by providing abundant O_2 in the range of 5.10–32.40 mol day^{-1} m^{-2}. The maximum rate (32.40 mol day^{-1} m^{-2}) of CH_4 oxidation was higher than reported (18.13 mol day^{-1} m^{-2}), suggesting that excess substrate can strengthen the microbial activity of landfill cover soil. The relationship between the CH_4 oxidation rate and the ratio of CH_4/O_2 is shown in Fig. 7. As the ratio of CH_4/O_2 increased (from 0.3 to 1.0), the CH_4 oxidation rate showed dramatic improvement and then decreased rapidly with the ratio of CH_4/O_2 increasing from 1.2 to 1.6. There was a relatively narrow optimal region for the high CH_4 oxidation rate [32–35]. When the CH_4 concentration was less than 20%, CH_4 could be removed completely and then the CH_4 oxidation percentage decreased [35, 36].

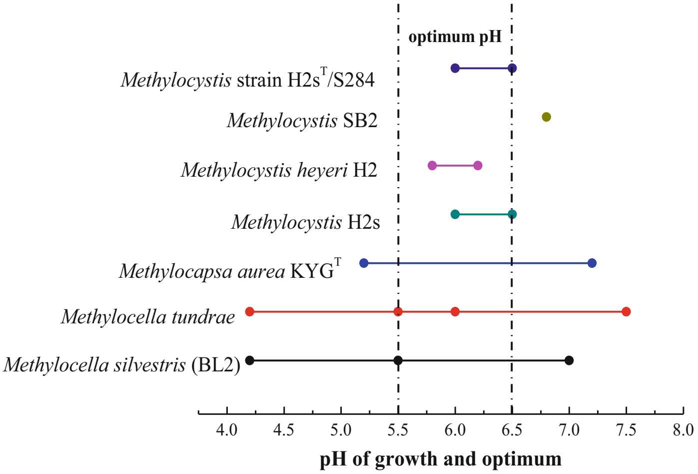

Fig. 5 Growth and optimum pH of facultative methanotrophs

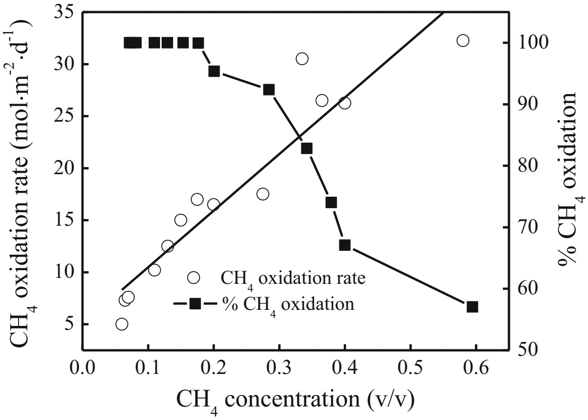

Fig. 6 CH_4 Oxidation rate and CH_4 oxidation percentage change with CH_4 concentration

CH_4 upward diffusion and air downward diffusion were regarded as the limiting factors for biological CH_4 oxidation [37], and 0.2–125 mol m^{-2} day^{-1} CH_4 was fluxed upward and ambient air diffused downward [38]. Accordingly, the vertical distribution patterns of CH_4, O_2, and CO_2 were recorded and shown in Fig. 8. CH_4 content increased with the depth, whereas O_2 content decreased. Unlike CH_4 and O_2, there was an obvious gradient in the distribution of CO_2 that the highest concentration of CO_2 occurred at the 20 cm depths, and the lowest concentration of CO_2 occurred at the surface.

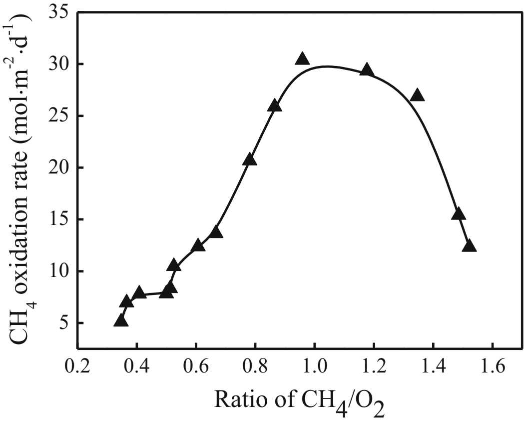

Fig. 7 Oxidation rate of CH_4 change with a ratio of CH_4/O_2

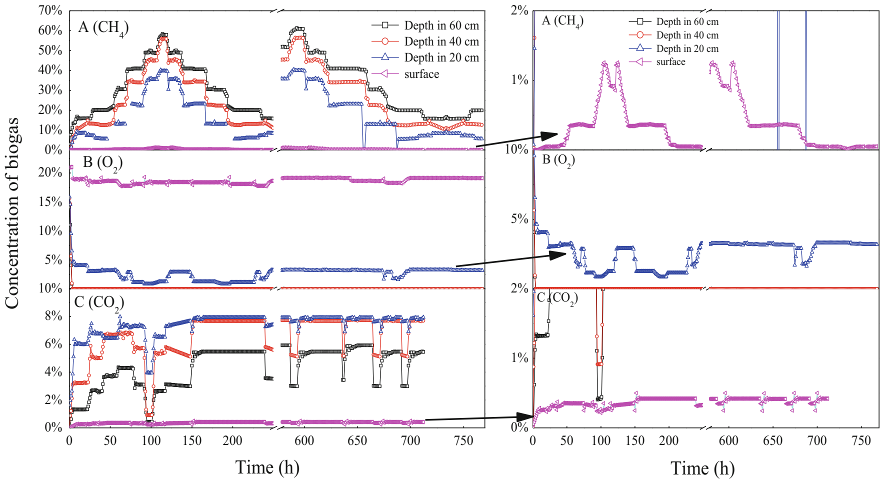

Fig. 8 Real-time monitoring of biogas at different depths of simulated landfill cover soil

The CH_4 concentration varied at the 20 cm (1.4–45.4%), 40 cm (6.0–54.7%) and 60 cm (14.0–57.9%) depths and increased with the increasing of the CH_4 flux (0.2–125 mol m^{-2} day^{-1}).

6 Conclusions

MSW is an important contributor for anthropogenic GHG emissions, and the tendency of GHG emissions was estimated. Around 72.4 million tons of $CO_{2\text{-eq}}$ emissions were released from the waste sector in China in 2013, while those in 1991 amounted to 10.95 million tons. Landfill predominated the GHG emissions, which increased to the peak of 82% (1999) and finally to 69.5% (2013). The GHG division in seven regions was calculated for the interval of 5 years, as waste disposal facilities increased markedly after 2003. The EC was the dominant region, while the occupied percentage decreased greatly from 39.6% (2003) to 26.4% (2013). The NW had a tremendous increase in CO_2 emissions due to the increase in MSW landfilling from 35.9 to 98.5%. Based on the bottom-up calculation method, around 1.48 Mt CH_4 might be released from the 1955 landfills in 2012, 24.88% higher than in 2007. The geographic distribution of CH_4 emissions changed with the mitigation measures' implementation and the improvement in local conditions. More efforts should be emphasized for CH_4 abatement in landfills, and the landfill managers should differentiate among CH_4 mitigation measures for landfills. To reduce CO_2 emissions, the implementation of "PAYT" and the environmental protection tax might be two potential ways to drive the source reduction of MSW generation. The application of the MSW sorting system by the trammel screener at a 40 mm mesh size is the promising pretreatment method for GHG emissions reduction for an incineration plant. CH_4 oxidation through landfill soil cover is one of the promising ways for landfills. The changing of methanotroph activity led to the gradient of the CH_4 oxidation rate in landfill cover. The dominant microorganisms at the phylum level were *Proteobacteria* and *Bacteroidetes*, and the dominant methanotrophs were *Methylobacter*, *Methylococcales*, and *Methylocystis* after CH_4 incubation.

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