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REGIONAL CASE STUDY

Mitigating greenhouse gas emissions of municipal solid waste management system: case study of Chengdu, China

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Abstract
Municipal solid waste management has become a worldwide concern. Chengdu municipality has decided to adopt the "zero landfilling" strategy for local waste management after 2020. In this study, life cycle assessment is performed to identify the potentials of reducing greenhouse gas emissions in Chengdu. The results of this study showed that net greenhouse gas emission of the current municipal solid waste management system is estimated to be 1,775,000 metric tons of CO_2 equivalent. Furthermore, if incineration is to be the primary waste end-life disposal method, it is critically important to exclude plastic wastes from incineration wastes and improve the energy recovery efficiency, while the landfilling with landfill gas collection still can be a good option for MSW disposal, or expanding the processing capacity of composting plant, to achieve the better outcomes of greenhouse gas mitigation. The results indicate the high potential of reducing greenhouse gas emissions of the local municipal solid waste management system, and detailed recommendations for further improvements on local municipal solid waste management system are proposed at the end of this study, which could be the reference for municipal solid waste management practice in both Chengdu and other cities in China.

Keywords Municipal solid waste management · Life cycle assessment · Greenhouse gas emission

Abbreviations

MSW	Municipal solid waste
GHG	Greenhouse gas
LCI	Life cycle inventory
LCA	Life cycle assessment
HDPE	High-density polyethylene

Introduction

In recent decades, the rapid growth of the global economy has brought about a large quantity of municipal solid waste (MSW) which turned into a worldwide concern. Due to the significant risks to the natural environment and public health caused by inappropriate handling of MSW, the importance of proper management of MSW has been widely recognized by governments [1]. However, MSW management service is considered intensive, as it requires not only the strenuous efforts of municipalities but also close corporations between relevant stakeholders [2].

Nevertheless, the practice of MSW management highly varies in different regions, owing to the diverse composition of MSW, local waste management strategies, as well as the availability of corresponding infrastructures and technologies [3]. For instance, research by Sharma et al. on MSW management system in Himachal Pradesh, India found that the poor performance is caused by the ineffective waste collection, inadequate treatment capacity, and the lack of 3R's facilities, whereas the better case was observed in Southern Italy owing to the availability of corresponding infrastructures and proper MSW management practices [4, 5]. As the world's biggest developing country, China has been encountering the unprecedented MSW problem in recent years because of the rapid growth of population and economic conditions [6]. In 2004, China had become the world's largest wastes producer [2]. Previous research of China found several limitations on the MSW management practice, including the waste collection system, energy recovery incineration, landfill management, waste recycling, disposal, etc. [7].

Generally, approximately 3% of global greenhouse gas (GHG) emissions are directly generated from the treatment

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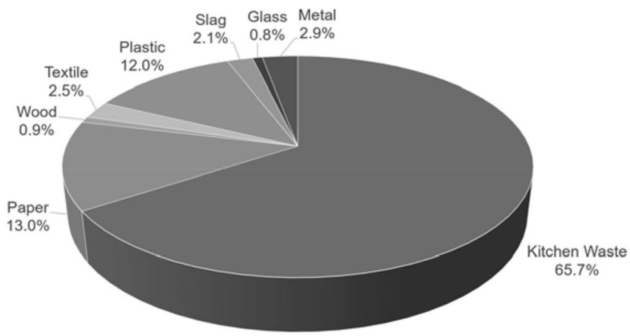


Fig. 1 Composition of MSW in Chengdu

of wastes, but the significance of the waste sector for reducing global GHG emission has been underestimated, due to the lack of the corresponding quantification of GHG mitigation when making waste management decisions [8, 9]. As an effective tool for supporting decision-making, life cycle assessment (LCA) has been widely applied in the field of MSW management [10]. Although there has been a variety of researches on MSW management based on LCA [11–13], the specific regional case study is still meaningful, because of the variation of MSW management systems and the overall effects resulted from that [14]. Hence, being one of the megacities in China, Chengdu is selected as the case for this study, to investigate the potentials of mitigating GHG emissions of the local MSW management system from a life cycle perspective.

Materials and method

MSW in Chengdu

Chengdu is the capital city of the Sichuan province, China, with a total of 20 districts covering an area of 14,335 km^2, and the residential population of Chengdu is around 14.35 million [15]. In 2017, about 5.43 million tons of MSW were produced in Chengdu (ranking fifth in China), indicating that the per capita generation of MSW is nearly 1.04 kg/day [16]. However, the figure is still rising owing to the increase in population and the development of the local economy. Statistics demonstrated that the annual growth rate of local tourism and the real estate sector is around 15%, while that of the manufacturing industry is 7.8% [17].

The composition of MSW in Chengdu is collected from relevant research by Yang et al. as illustrated in Fig. 1, indicating the high proportion of organic components in MSW [18].

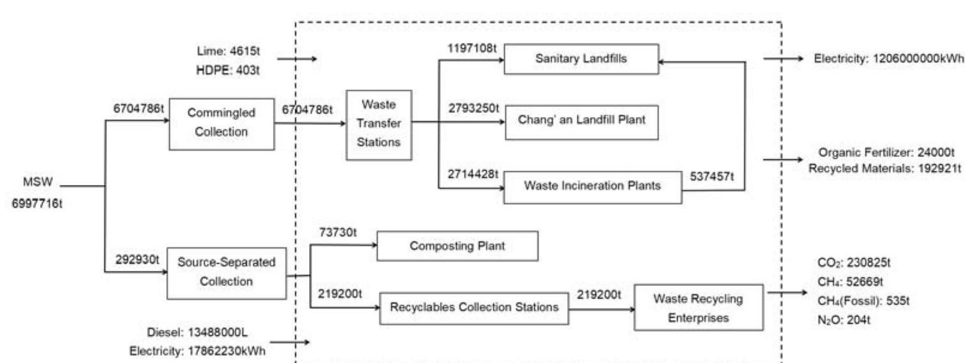
MSW management in Chengdu

At present, the Environmental Sanitation Management Office of Chengdu Municipal Administration Bureau is responsible for the management of MSW, including waste collection, transport, and end-life disposal. In 1995, the national government of China promulgated the "Law of the People's Republic of China on the Prevention and Control of Solid Waste Pollution", which established the national solid waste management strategy based on three main emphases: harmless treatment, waste reduction, and the recycling and reuse of wastes. At the local level, Chengdu follows the national solid waste management strategy, combining different MSW processing and treatment methods into an integrated system as shown in Fig. 2.

Waste collection

In April 2018, Chengdu municipal government issued the "Implementation plan for Source-Separated MSW Collection in Chengdu (2018–2020)" to develop a source-separated MSW collection system for promoting the recovering and recycling rate, and MSW is required to be sorted out and discarded into four types waste collection bins, including the kitchen waste, recyclable wastes (including paper, plastics, textile, metal, and glass), hazardous waste, and other wastes. Nevertheless, similar to the industrial waste, the hazardous waste (mainly including medical wastes,

Fig. 2 The current MSW management system in Chengdu, with material and energy flows, which is identified through the filed work, while the dotted line represents the system boundary of this study



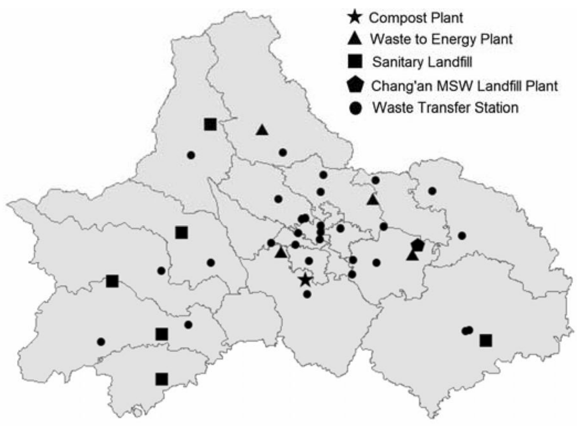


Fig. 3 Waste transfer stations and end-life disposal plants in Chengdu, which is investigated through the filed work

chemical substances, and electronics wastes) is collected and treated by professional hazardous wastes treatment companies with corresponding licenses, hence the industrial and hazardous wastes managements are not considered in this study as they are separated from local MSW management system [19, 20]. As of August 2019, only around 53% of households had covered with classified garbage bins, hence both commingled and separated MSW are gathered at the city level at present. Since the commingled waste is discarded into the garbage bins, it is manually collected and transported to the nearest waste transfer station by sanitation workers using electric or manpower tricycle [21, 22]. Source-separated kitchen waste and recyclables are transported directly to the composting plant and local recyclables collection stations.

Waste transfer

At the waste transfer station, commingled wastes will be compacted and transported to end-life disposal plants by garbage trucks. In the existing MSW management system, there are a total of 30 registered waste transfer stations under the management of the Chengdu Municipal Administration Bureau, as presented in Fig. 3. Unregistered and informal waste transfer services are not considered in this study.

End-life disposal

So far, there are 12 waste disposal plants in Chengdu, including four waste incineration plants, one composting (aerobic digestion) plant, six sanitary landfill sites, and one landfill plant with landfill gas utilization facilities, as demonstrated in Fig. 3. The composting plant produces 24,000 tons of humic acid organic fertilizer annually [23]. All four waste incineration plants are fitted with energy recovery facilities, with annual electricity generation[1] of 1.04 billion kWh in total, while the landfill named "Chang'an MSW sanitary landfill plant" is equipped with landfill gas utilization facilities, producing approximately 166 million kWh of electricity per year, while the landfill gas collection efficiency is 85% [24–26]. The bottom ash generated during waste incineration process is handled by landfill, while the discharged leachate is processed within waste disposal plants. The open dump is not considered in this study, as less than 1% of MSW was disposed of in this approach [27].

Goal and scope definition

Goal and functional unit definition

The goal of this study is to understand the potentials of mitigating the GHG emissions of the local MSW management system when altering the current MSW management practice. Therefore, the functional unit is defined as the management of the total amount of MSW generated within the 1-year period (from August 2018 to August 2019) to investigate the effects of managing the same amount of MSW through different MSW management practices.

System boundary

As shown in Fig. 2, the processes included within the boundary of this study are waste transfer, transport, recycling, and end-file disposal. As the collection of MSW is implemented by manual labor, it is not involved in the scope of this study. Besides, the upstream processes of manufacturing and product using are excluded as well, which could result in the lower results from LCA, because the GHG emissions from those processes are not calculated. MSW is the primary input to the system, while other inputs including the energy and ancillary materials are inevitable demands for system operation. And in terms of the outputs other than GHG emissions, namely the recycled materials, compost, as well as the electricity, are considered to be substitutions to avoid the environmental burdens of the production of electricity and original products.

Life cycle inventory

Scenario setting

Scenario A (SA) Scenario A represents the existing MSW management system in Chengdu. MSW disposal data were

[1] The electricity generated by landfill plant and waste to energy plants is the net electricity output to the power grid, which had deducted the energy consumption for the operation of the treatment plant, leachate treatment, treatment process, etc.

collected from the Chengdu Municipal Administration Bureau. From August 2018 to August 2019 (12 months), a total of 6,997,716t MSW were collected for further treatment. Of these MSW, 2,714,428t MSW was incinerated, 3,990,358t MSW was disposed of in landfills (nearly 70% were treated in the "Chang'an landfill plant"), 73,730t kitchen waste was composted producing 24,000t organic fertilizer, and 219,200t recyclables were collected for recycling. Average transport distances to composting plant and other waste disposal plants are 10 km and 35 km, respectively, while the distance to recyclable collection stations is assumed to be 10 km. Incineration plants produce 1.04 billion kWh of electricity in total, while 166 million kWh is generated from the landfill plant with the 85% landfill gas collection efficiency. And to guarantee the consistency of the results, the same MSW data introduced above are to be used in all following the scenarios.

Scenario B (SB) Since no appropriate site is available in Chengdu for the new landfill from 2020, Chengdu Municipal Administration Bureau decided to adopt the "zero landfilling" strategy, planning that the primary MSW will be handled through the incineration, composting, and recycling [28], the processing capacity of the composting plant will be raised to 2,179,050t annually [29], thus hypothetically 709,307t organic fertilizer is to be produced. 413,585t recyclables are assumed to be collected when the covering rate of the classified waste bin increased from 53 to 100%. And theoretically, since the remnant MSW (4,405,081t) is to be incinerated, the electricity generation is considered to be increased to approximately 1.69 billion kWh.[2]

Scenario C (SC) In this scenario, a hypothesis is made that the local MSW management system will still adopt the landfill approach to dispose of MSW. Hence in this scenario, still 2,714,428t MSW will be incinerated producing 1.04 billion kWh electricity (the same as scenario A), while 413,585t recyclables and 2,179,050t kitchen wastes will be recycled and composted, respectively (the same as scenario B). Given that no appropriate site is available for landfills in Chengdu, it is assumed that the remnant MSW (1,690,653t) will be transported to the landfill in another city, thus the transport distance is assumed to be increased to 100 km. And theoretically, about 54 million kWh electricity can be produced to power grid from the landfill plant still with the 85% landfill gas collection efficiency, on account of the decline of biomass fractions that generate the landfill gas in the amount of MSW to be disposed of in the landfill plant.

[2] The assumption about the increase in collected recyclables, compost production, and electricity generation is based on the existing collection and production efficiency.

Scenario D (SD) In this scenario, it is assumed that the quantity of collected recyclables is to be doubled based on Scenario B, to examine the effectiveness of mitigating GHG emissions through waste recycling. Hence, 827,170t recyclables are assumed to be recycled, 3,991,496t are incinerated, and other figures remain the same as scenario B. Accordingly, the electricity generation is assumed to be decreased to about 1.53 billion kWh, as the incinerated MSW reduced owing to the increase in collected recyclables.

Life cycle inventory data

With regard to the life cycle inventory (LCI) data, that of waste incineration, landfill, and composting were gathered from the default data in the Ecoinvent 3.6 database [30]. However, to improve the accuracy of the results of this study, some life cycle inventory data were collected from the available database and previous relevant studies, which are specifically based on the reality in China. The heavy-duty vehicle emission data for waste transport is collected from the research by Li et al. [31], and the previous study indicates that the energy consumption of the waste transfer station is 1.92 kWh when processing 1 ton of MSW [32]. In terms of the waste treatments, disposing of 1 ton of MSW by incineration requires 1.7 kg lime and 2.22L diesel, while 198 kg of clinker are generated to be treated in landfills, landfilling 1 ton of waste consumes 1.87L diesel, 1.92kWh electricity,[3] and 0.0625m^2 HDPE membrane (1.5 mm), and 28.62kWh electricity is needed for processing 1 ton of kitchen wastes [32–34]. Besides, given that no specific LCI of disposing of kitchen waste through landfill process is available in the Ecoinvent 3.6 database, corresponding data is collected from the research by Xu [35]. And the life cycle inventory data of electricity, diesel, lime, and HDPE production were collected from the CLCD database by Sichuan University and IKE Environmental Technology CO., Ltd. [36].

Given that the composition of the waste fractions in each recyclable category and the recycling of each specific recyclable waste in the real situation can be fairly complex, while the accurate composition data regarding these recyclables are not available, thus a simplifying assumption is made based on previous research by Du [37], which is given in Table 1. Accordingly, the waste paper is deemed to be used for producing waste paper pulp to avoid the production of wood pulp, corresponding life cycle inventory data collected from the previous study indicated that 1 kg of waste paper can produce 0.8 kg waste paper pulp [38].

[3] Electricity consumption of MSW landfilling is not calculated in the case of the landfill plant equipped with the landfill gas utilization facility, as the produced electricity is the net electricity output to the power grid.

Table 1 The assumption about recyclables components in each recyclable waste category, corresponding avoid productions, substitution ratios, as well as their percentage used in each scenario of life cycle assessment

Fraction	Paper	Plastic	Metal	Glass	Textile
Amount (t) Percentage (%)	117747 (53.7%)	44510 (20.3%)	23617 (10.8%)	17089 (7.8%)	16237 (7.4%)
Recyclable components	Waste paper	Waste PE plastic	Metal scrap	Waste glass	Waste textile
Avoided production	Wood pulp	HDPE	Alloyed steel	Flat glass	Textile (50Cotton/50Polyester)
Substitution ratio	1:0.8	1:0.9405	1:0.6	1:0.45	1:0.995

Table 2 The life cycle inventory for the four scenarios in this study, including the input of energy and ancillary materials, and the output of GHG emission, electricity, fertilizer, as well as the recycled products

Item	Scenario A	Scenario B	Scenario C	Scenario D
Input				
Materials				
MSW (t)	6,997,716	6,997,716	6,997,716	6,997,716
Lime (t)	4615	7489	4615	6786
HDPE (t)	403	78	198	70
Energy				
Electricity (kWh)	17,862,230	71,917,340	71,917,340	72,218,429
Diesel (L)	13,488,000	9,779,280	9,187,551	8,861,121
Output				
GHG emissions*				
CO_2 (t)	230,825	1,024,373	134,961	493,816
CH_4 (t)	52,669	−4457	3198	−6900
CH_4 (Fossil)(t)	535	121	284	247
N_2O (t)	204	427	257	376
Energy				
Electricity (kWh)	1,206,000,000	1,687,753,088	1,094,040,407	1,529,293,037
Materials				
Fertilizer (t)	24,000	709,307	709,307	709,307
Recycled products (t)	192,921	364,002	364,002	728,004

*The negative value of GHG Emissions indicates the net reduction of corresponding emissions owing to the avoid production of electricity, fertilizer, and original products of recyclables

Then, metal scrap and glass recyclables are assumed to be added into the production of alloyed steel and flat glass, avoiding 60 and 45% of the burden from the production of original products respectively [39]. The waste plastic is assumed to be recycled to HDPE granulates, while the default data in the Ecoinvent 3.6 database shows that 1 kg waste plastic can produce 0.9405 kg recycled HDPE granulates. For the waste textile, it is assumed that mechanical recycling is applied for producing recycled textile to avoid the production of virgin textile (50 Cotton/50 Polyester), previous research by Shi et al. provided life cycle inventory data and the 5% loss is considered resulted from mechanical recycling process [40]. Accordingly, the life cycle inventory data of steel and HDPE production were collected from the CLCD database, and that of flat glass and textile manufacture were from relevant researches, respectively [41, 42]. Apart from that, considering that recyclables are commingled without further segregation when being collected, the re-sorting process is required before recycling. Accordingly, the energy demand for classifying 1t recyclables is 2.648kWh electricity [43]. Furthermore, the humic acid organic fertilizer produced by the composting plant is assumed to avoid the same amount of organic fertilizer produced by livestock manure and rice chaff, the life cycle inventory data were gathered from research by Ji et al. [44]. Hence, the life cycle inventory for each scenario is presented in Table 2. And the uncertainties resulted from the assumption are to be discussed in the sensitivity analysis section of this study.

Life cycle assessment method

In this study, the LCA was performed using OpenLCA 1.9 software based on the CML-IA method [45], while the

Table 3 Characterisation factors of the CML-IA method applied in LCA of this study, indicating that 1 kg CH_4, CH_4(Fossil), and N_2O are equivalent to 28, 30, and 265 kg CO_2 respectively, with regard to their global warming potentials

GHG emission	CO_2	CH_4	CH_4 (Fossil)	N_2O
Characterisation factors (kg CO_2 Eq.)	1	28	30	265

GWP100a indicator was chosen for measuring the global warming potential for climate change. Hence, the characterisation factors of the CML-IA method are presented in Table 3. Furthermore, the allocation procedure is required to be given into consideration if the system involves multiple outputs when performing LCA [10]. So far, economic partitioning and substitution represent the major allocation approaches in many existing LCA studies related to MSW management [46]. However, relevant research indicated that the economic partitioning approach requires more accurate and regionalized data, which are not available for this study [47]. Therefore, the substitution method is applied to avoid the allocation method through system expansion, though it found that the results could be relatively low when applying this method [10, 46]. In addition, the CO_2 emission from biomass materials, such as kitchen wastes, paper, and wood, is viewed as short-cycle biogenic carbons emission, which would not disturb the balance of natural carbon cycle in the long term [46], hence the biogenic CO_2 emission are excluded from GHG calculation.

Results and discussion

Scenario results

The results of LCA on each scenario are summarized and presented in Figs. 4, 5, 6. Generally, it can be seen that the net GHG emissions of SC and SD are significantly lower than that of SA and SB. The outcome of SC reached only around 300,000 metric tons of CO_2 equivalent ($MTCO_2$ Eq.), which is less than 20% of GHG emissions of SA.

As introduced earlier, SA represents the current MSW management practice in Chengdu, the results showed that the direct GHG emissions released from the local MSW management system are around 3,045,000 $MTCO_2$ Eq. in total. As 1,270,000 $MTCO_2$ Eq. GHG is estimated to be avoided by electricity generation, MSW recycling, and compost production, hence the net GHG emission of SA is 1,775,000 $MTCO_2$ Eq. In this case, the direct GHG emissions from MSW transport and transfer processes are around 22,000 $MTCO_2$ Eq. and 9,500 $MTCO_2$ Eq., respectively, which even can be deemed negligible in comparison with that of end-life disposal. However, research by Song et al. [48] found that 8% GHG emission can be reduced if altering

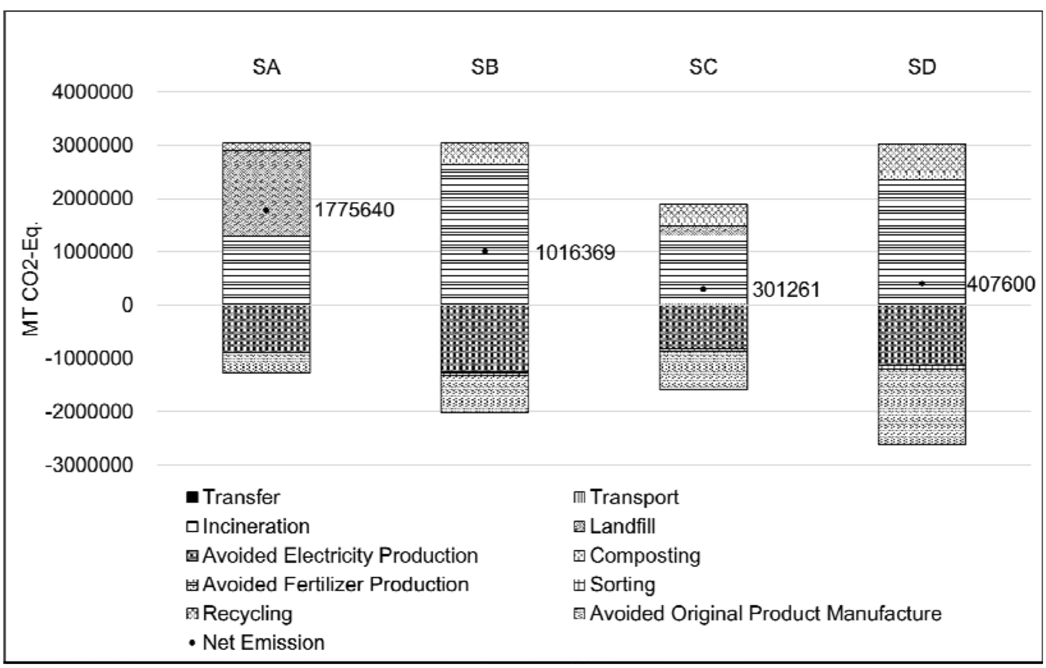


Fig. 4 Comparison of GHG emissions of each scenario. It shows the total GHG emissions of each scenario, involving the value of related processes in the MSW management system. The net emission of each scenario is calculated by subtracting avoided emission (negative value) from the total emission (positive value)

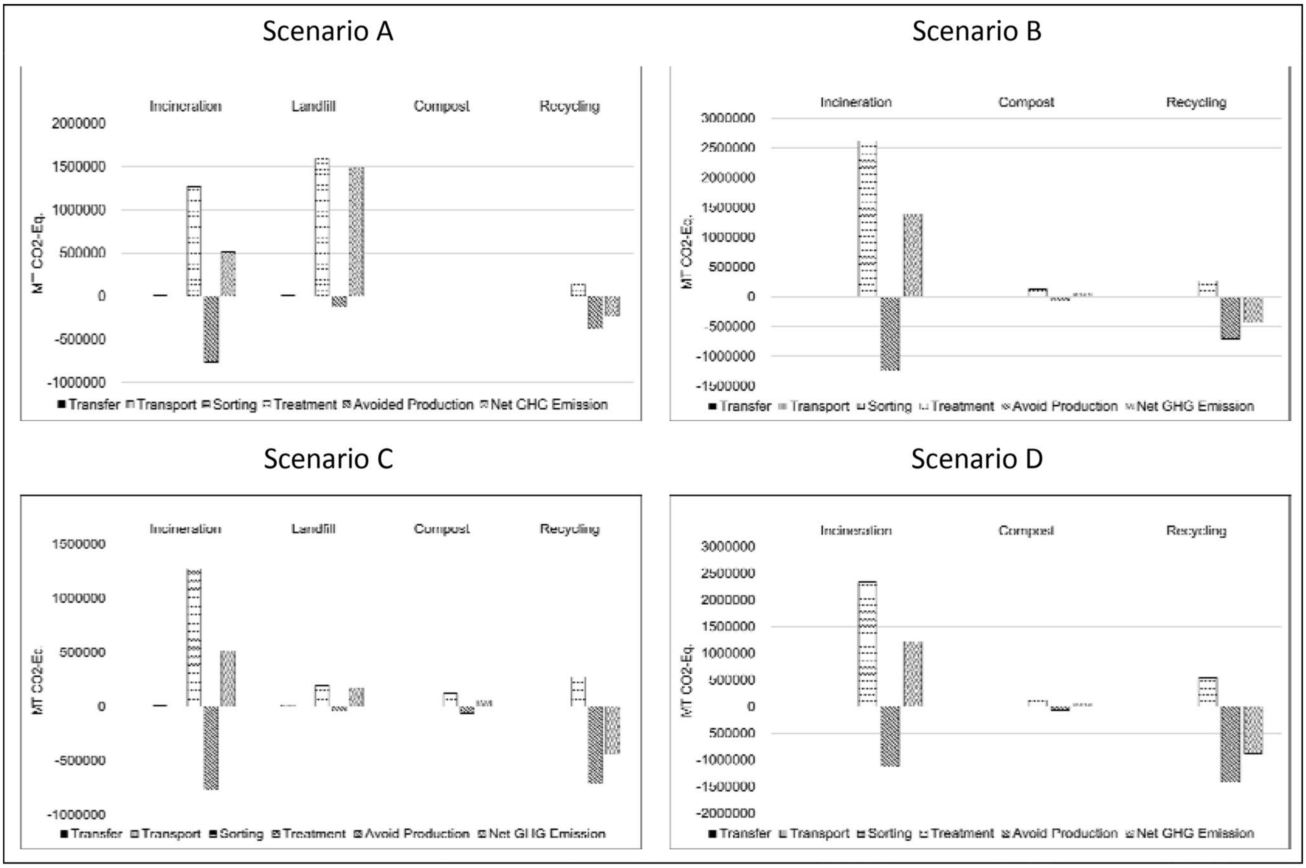


Fig. 5 The GHG emissions of related processes in each scenario, the negative value indicates the GHG emissions avoided by the process

the fuel for heavy-duty vehicles to liquefied natural gas from diesel, which can be an alternative for reducing GHG emission of MSW transport. Furthermore, around 430 $MTCO_2$ Eq. GHG resulted from the re-sorting process can be also avoided if recyclable wastes will be collected separately. Besides, it is found that the majority of direct GHG emissions are produced by MSW incineration and landfill, with 42 and 53%, respectively, while kitchen waste composting only contributed around 1.4%. In this case, the net GHG emission of MSW Incineration is only around 512,000 $MTCO_2$ Eq., because over 60% of direct GHG emissions are estimated to be offset by electricity generation. In contrast, the electricity generated by the MSW landfill can only offset less than 8%, thus the net GHG emission of it is nearly 1,500,000 $MTCO_2$ Eq. Although recyclables only account for 3% of the amounts of MSW in total, approximately 232,000 $MTCO_2$ Eq. GHG can be avoided by them, which is equivalent to nearly 12% of the total net GHG emission of MSW incineration, landfilling, and composting.

In SB, since the landfilling is abandoned, the environmental burden of clinker landfilling is distributed to the MSW incineration process. Compared with SA, the net GHG mission of SB drastically dropped to 1,016,000 $MTCO_2$ Eq. In this case, the direct GHG produced from the MSW management system slightly declined to 2,767,000 $MTCO_2$ Eq. without considering the avoided GHG emissions by MSW recycling. And the net GHG emission of kitchen waste composting increases to 57,000 $MTCO_2$ Eq., while the avoided GHG emission of recycling reaches nearly 437,000 MT CO_2 Eq. Moreover, it is worth noting that more than 95% of direct GHG emissions are contributed by MSW incineration (around 2,623,000 $MTCO_2$ Eq.). And of these GHG emissions, over 72% are discharged by the incineration of plastics, despite waste plastics only account for 17.2% of incinerated MSW.

In SC, landfilling is adopted again, hence a noticeable rise is observed in the GHG emission of transport. However, the net GHG emissions of SC decreased to around 300,000 $MTCO_2$ Eq., accordingly reduced 1,474,000 $MTCO_2$ Eq. and 715,000 $MTCO_2$ Eq. in comparison with SA and SB. In SA, merely 70% of MSW is disposed of in Chang'an landfill plant with landfill gas collection. In this case, it is found that the direct GHG emissions of them are only around 412,000 $MTCO_2$ Eq., as 85% of direct GHG emissions are collected. And since the remaining 30% of MSW are landfilled without landfill collection, substantial amounts of GHG are directly

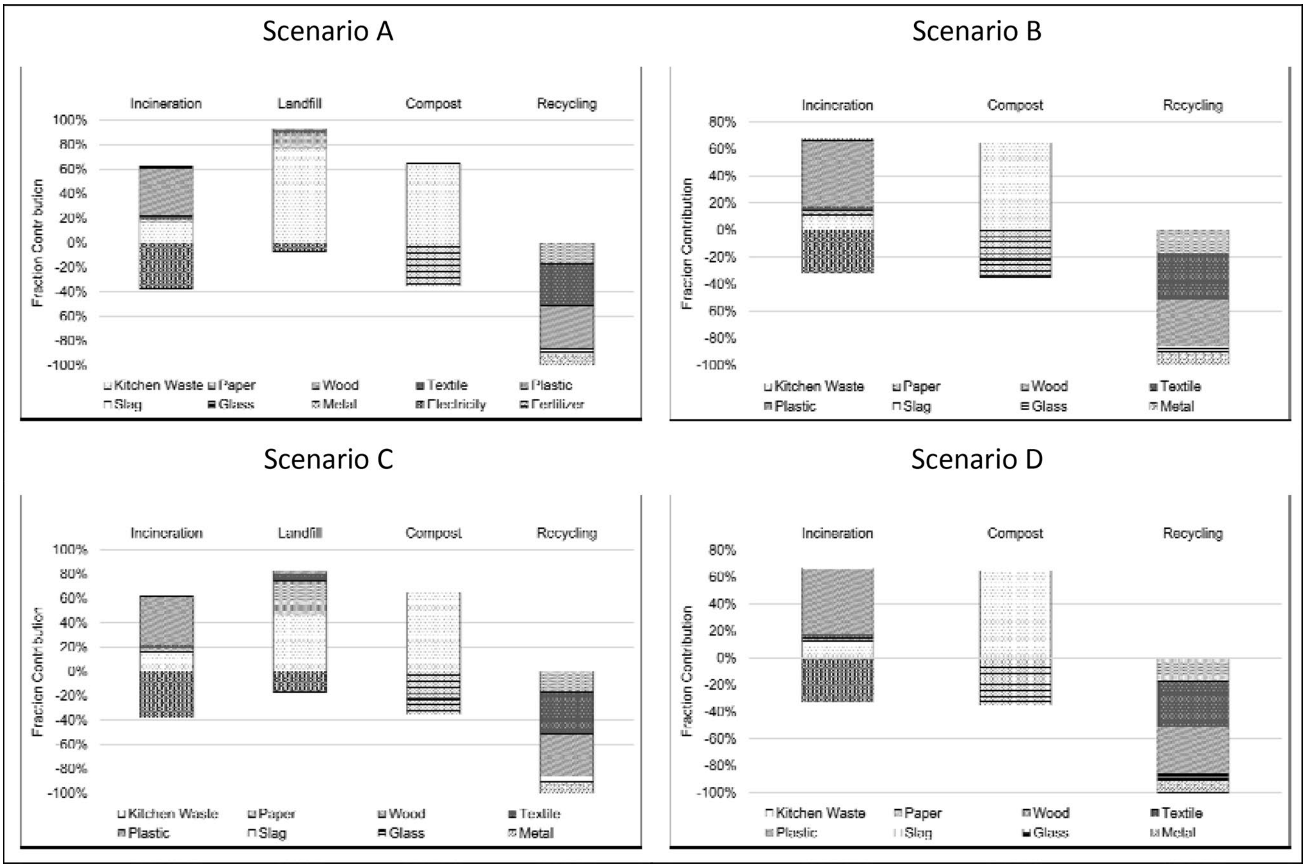


Fig. 6 The percentage contribution of different MSW components to GHG emissions resulted from four waste treatment methods in each scenario, the negative value means the percentage contribution to the GHG emissions avoided by each treatment method, while the total value reaches to 100% indicating the GHG emissions from treatment process without considering the GHG emission from transport and transfer

discharged into the atmosphere, with nearly 1,178,000 $MTCO_2$ Eq. But in SC, only about 191,000 $MTCO_2$ Eq. GHG emissions are discharged with the 85% landfill gas collection efficiency, because the amount of kitchen wastes treated by composting increased from 73,730t in SA to 2,179,050t, thus less methane is generated and discharged into the atmosphere from the landfill plant, though less electricity is produced. And in this case, the net GHG emission of waste composting only increased by around 55,000 $MTCO_2$ Eq. If the landfill plant in SC is not fitted with any landfill gas collection facility, the direct GHG emission will rise to approximately 1,262,000 $MTCO_2$ Eq., despite that the total amount of MSW landfilled reduced nearly 58% in comparison with SA. Hence, it can be seen that the landfill gas collection is of great significance when adopting the landfilling approach for MSW disposal. Otherwise, composting could be a better option to treat biomass fractions in MSW for GHG emissions reduction, even though it requires more energy input. Considering the outcomes of SA, SB, and SC, it implies that the landfill method still could be worth applying if landfill gas can be collected, because the direct GHG emissions can be even lower, and there are still clinkers from MSW incineration needed to be treated in landfills.

Then, in SD, the net GHG emission is less than 408,000 $MTCO_2$ Eq., which is mainly owing to the avoidance of a substantial amount of GHG emissions contributed by recycling, though less electricity is generated than SB. Although recyclables only make up approximately 11.8% of MSW in total, 875,000 $MTCO_2$ Eq. GHG is estimated to be avoided by them. The results of SD demonstrated that promoting MSW recycling is of great significance for reducing GHG emissions. And relevant research by De Feo et al. [5] found that if recyclable wastes can be collected and recycled adequately, the avoided GHG emissions by MSW recycling will offset the whole direct GHG emissions of MSW management system, thus the net GHG emission can reach the negative value.

Furthermore, each type of MSW component releases varying GHG emissions when being disposed of through different MSW disposal approaches. In SA, waste plastics contribute the largest proportion (63.5%) to GHG emissions of MSW incineration, followed by kitchen waste, paper,

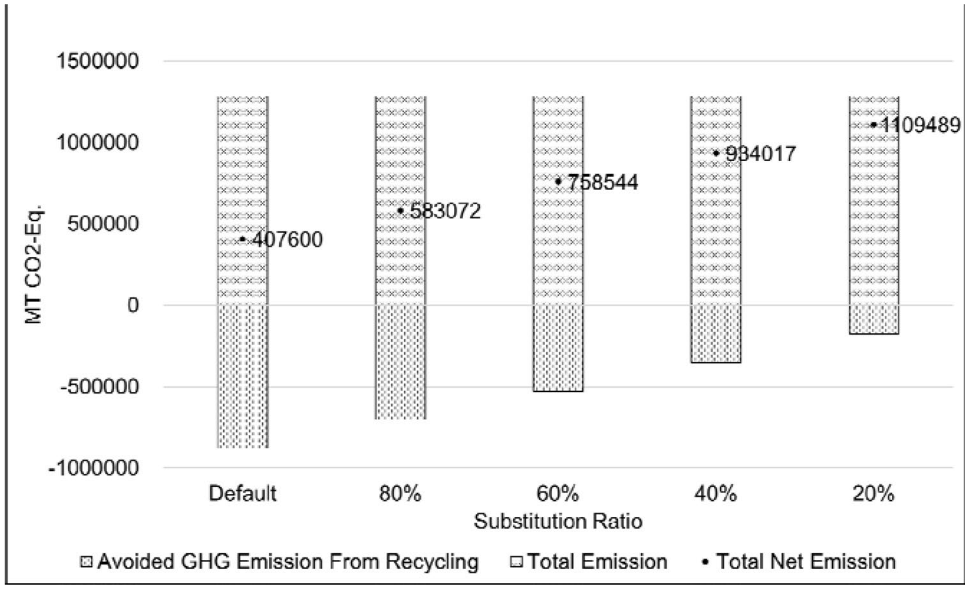


Fig. 7 The comparison of GHG emissions of MSW recycling under different substitution ratios based on Scenario D. The total emission involves the GHG emissions generated from all the related MSW handling processes in Scenario D, while the total net emission represents the value after the deduction of GHG emissions avoided by MSW recycling, and the negative value indicate the amount of GHG emission avoided by the MSW recycling

and textile, constituting 25.7, 4.5, and 4.1%, respectively. Regarding the MSW landfill, kitchen wastes and paper bring out over 96% of GHG emissions in total. However, unlike plastics, the GHG emissions of those biomass fractions are mainly the methane produced by anaerobic digestion in landfills. On the contrary, the incineration of plastics will directly discharge huge amounts of CO_2 into the atmosphere [49], thus the landfilling can be a better end-life disposal option for plastics when GHG emission reduction is considered the primary concern in local MSW management. Based on the results of LCA, the amount of GHG released by incineration is about 27 times that of the landfilling when disposing of the same quantity of waste plastics. Consequently, it implies that if the landfill approach is to be abandoned, separating out plastics from MSW to incineration is of crucial importance to deal with corresponding GHG emissions to the atmosphere. Then, GHG emissions of metal and glass by landfilling can be deemed negligible as these components are mainly inert wastes, hence the environmental burdens of them primarily resulted from corresponding energy and ancillary materials consumption. For the textiles, the GHG from incineration is mainly the CO_2 released from synthetic fibers in textiles, while methane represents the primary source of GHG from landfills [50].

With regard to material and energy recovery, the results of LCA showed that avoided GHG emission from electricity generation of MSW incineration is evidently larger than that of MSW landfill, the main reason is that energy recovery efficiency of MSW landfill is lower than that of MSW Incineration. Similar outcomes were also observed in previous studies targeted on the China region [46, 51, 52], indicating that MSW incineration can be a better choice for implementing energy recovery. Then, the recycling of plastics, textile, and paper play the most significant role in avoiding GHG emissions, with proportions of 34.6, 34.4, and 17.2%, respectively.

By and large, the outcomes of this study introduced above indicate the high potential of GHG mitigation through improving existing MSW management practices. And the uncertainty resulted from MSW recycling is to be discussed in-depth in the sensitivity analysis section.

Sensitivity analysis

Substitution ratios

In reality, the substitution ratio is highly variable, depending on the recycling technologies applied. Despite the substitution ratios applied in LCA were collected from previous researches representing the real situation of MSW recycling in China, it is still necessary to conduct sensitivity analysis to verify the effectiveness of reducing GHG emission through waste recycling under different substitution ratios. Therefore, an evaluation is performed based on SD, and it is assumed that the substitution ratio declines to 80, 60, 40, and 20% of the original basis.

As shown in Fig. 7, the avoided GHG emission gradually declines as the substitution ratio decreases. Consequently, the total net GHG emission constantly increases from around 408,000 MT CO_2 Eq. to 1,109,000 MT CO_2 Eq., exceeding the net GHG emission of SB. The results indicate that the substitution ratio can evidently affect the performance of MSW recycling regarding its GHG reduction effect. If the substitution ratio is only 20% of the original basis, the amount of avoided GHG turns out to be 175,000 MT CO_2

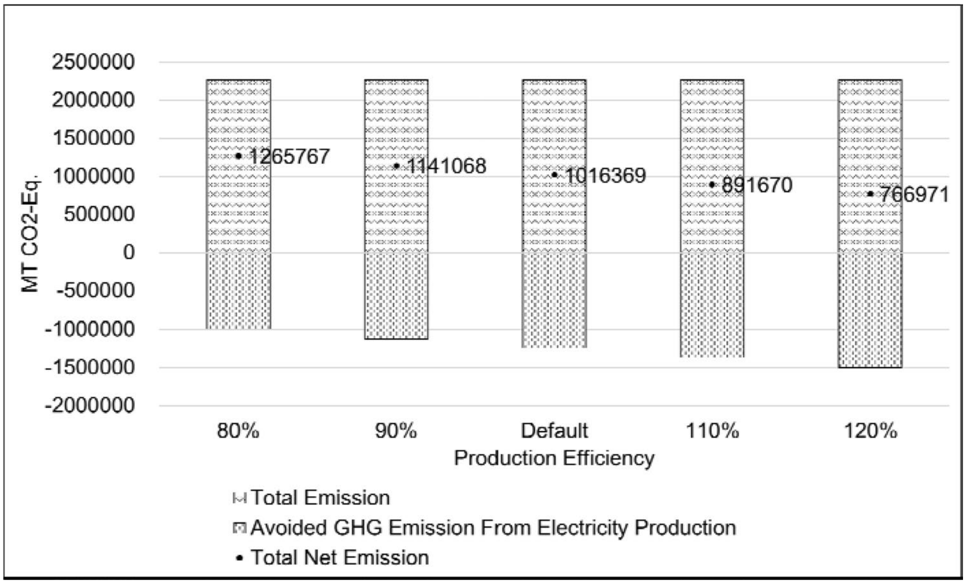


Fig. 8 The comparison of GHG emissions of electricity generation under different production efficiency based on Scenario B. The total emission involves the GHG emissions generated from all the related MSW handling processes in Scenario B, while the total net emission represents the value after the deduction of GHG emissions avoided by electricity production, and the negative value indicates the amount of GHG emission avoided by electricity generation

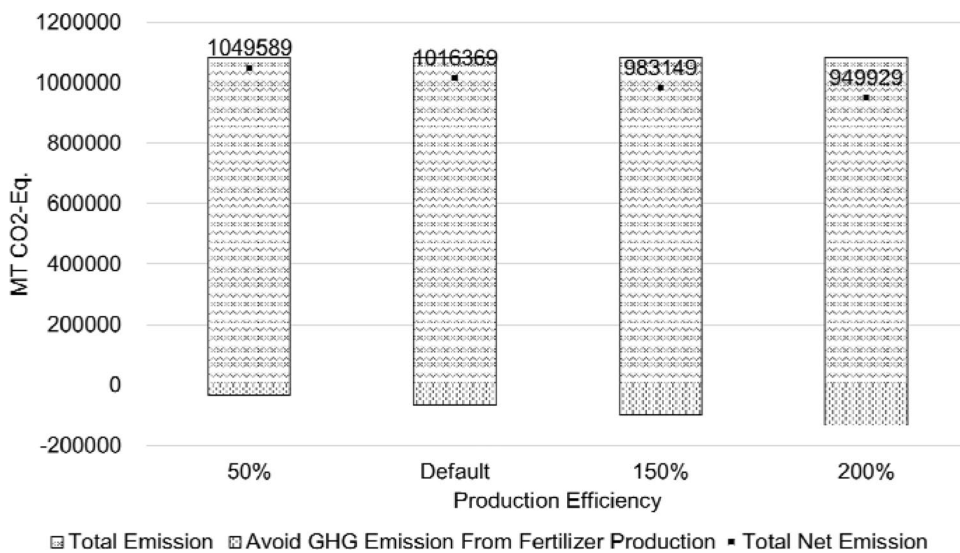


Fig. 9 The comparison of GHG emissions of compost production under different production efficiency based on Scenario B. The total emission involves the GHG emissions generated from all the related MSW handling processes in Scenario B, while the total net emission represents the value after the deduction of GHG emissions avoided by compost production, and the negative value indicates the amount of GHG emission avoided by compost generation

Eq. In this case, the avoided GHG is far less than that of SA, indicating that the efforts made on facilitating recyclable collection can be wasted. Therefore, the results imply that when performing MSW recycling practice, it is meaningful to take the performance of recycling technology into consideration, paying more attention to the adoption of appropriate technologies that have minimum costs in the recycling process. For instance, relevant research by Wu [53] found that recycling waste plastics through catalytic cracking technology would release over 1-time extra GHG than applying the granulation method. Nevertheless, it does not mean that improving the recycling rate is pointless. If more recyclable wastes can be collected, there will be less remnant MSW for disposal, which could alleviate the burden of the local MSW management system and reduce corresponding GHG emissions. Both recyclable rate and substitution ratio can be important for improving MSW recycling performance.

Electricity generation, landfill gas collection, and compost production efficiency

In SB, the electricity generation and compost production are estimated based on existing production efficiency. Consequently, a sensitivity analysis is conducted based on SB to understand the influence caused by corresponding uncertainties. In this case, the electricity and compost production efficiency are considered varying from 80 to 120%, and 50 to 200%, respectively. Hence, the results are presented in Figs. 8 and 9.

It can be seen from the results that when the electricity production efficiency drops to 80% of the original basis, the

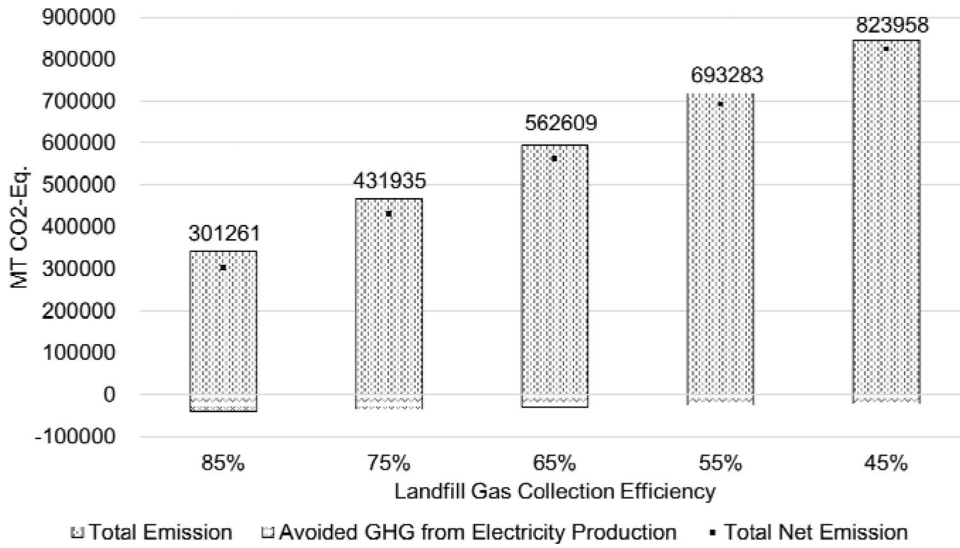


Fig. 10 The comparison of GHG emissions under different landfill gas collection efficiency based on Scenario C. The total emission involves the GHG emissions generated from all the related MSW handling processes in Scenario C, while the total net emission represents the value after the deduction of GHG emissions avoided by electricity production, and the negative value indicates the amount of GHG emission avoided by electricity generation

net GHG emission of SB reaches approximately 1,266,000 MTCO_2 Eq., exceeding that of SA and SC. Accordingly, when it increases to 120%, the net GHG emission declines to 767,000 MTCO_2 Eq. Hence, it is found that the variation of electricity generation efficiency can result in substantial changes in GHG emissions of the MSW management system. On the contrary, the compost production efficiency influences the outcomes less, as only around 33,000 MT CO_2 Eq. more GHG will be released when the compost production efficiency declines to 50% of the original basis.

Besides, the same landfill gas collection efficiency as SA is adopted in SC, hence a sensitivity analysis is also conducted in this regard based on SC. In this case, the landfill gas collection efficiency is assumed to be declined from 85 to 45%.

As can be seen from Fig. 10, when the landfill gas collection efficiency drops from 85 to 45%, the amount of GHG discharged will significantly increase, while the electricity generation will reduce. Hence, the net GHG emissions can be increased substantially, from around 300,000 MTCO_2 Eq. to 824,000 MTCO_2 Eq. It indicates that the landfill gas collection efficiency has considerable influence on the net GHG emissions, thus maintaining a high collection efficiency can be critically important when adopting the landfill method in MSW management system. Besides, the results also indicate that when Chengdu municipality plans to entirely rely on incineration to dispose of MSW, it is crucial to pay attention to the installed electricity generation capacity of MSW incineration plants to cut down GHG emissions from MSW management system to the maximum extent.

Choice of recycling and substitution products

As mentioned earlier, the constitution of recyclable components in each recyclable waste category and the choice of corresponding recycling method can be fairly complex in the reality, depending on the purpose of the recycling and the characteristics of recycled materials, hence a simplifying assumption is made to conduct LCA. In this study, the recycling of paper only considered the production of wood pulp, whereas the contribution of wood for GHG mitigation was not involved in LCI. If doing so, another 1.472MT CO_2 Eq. GHG then can be deduced owing to the wood conservation [36]. Similarly, the substitution product for organic compost in LCA is considered to be organic fertilizer. If choosing chemical fertilizer (carbamide fertilizer) to the corresponding substitution product, approximately 1MT CO_2 Eq. more GHG can be avoided then. Moreover, mechanical recycling is the common approach of recycling textile wastes in China [40], as the reuse of textiles tends to be more valuable than recycling, due to the difficulty and complexity of recycling natural fibers, and less GHG can be avoided when applying chemical recycling methods [50, 54]. In this study, waste glass and metal are viewed as secondary materials to be added into the manufacturing of original products, while the plastic waste is processed to recycled granulates. Similar to the recycling of textile wastes, the reuse of these recyclable can avoid the corresponding environmental burden of the recycling process, and relevant research showed that recycled plastic granulates and fibers tend to have lower strength, being commonly used for producing other relatively low-quality plastic products [55]. Therefore, despite the net GHG emission can reach negative values when recyclable wastes in MSW can be recycled substantially, it still can be meaningful if the local municipality could consider establishing corresponding strategies and infrastructures for stimulating the reuse of waste products, which could contribute to maximizing the effects of GHG mitigation of local MSW management.

Conclusion and recommendations

In this study, the GHG emissions of the existing MSW management system in Chengdu are estimated. The direct GHG emissions from the local MSW management system are 3,045,000 MT CO_2 Eq. in total, while 1,270,000 MT CO_2 Eq. GHG is estimated to be avoided by MSW recycling, electricity generation, as well as compost production. Hence, the total net GHG emission of the current MSW management system is expected to be 1,775,000 MT CO_2 Eq. Moreover, based on the results of four different scenarios in this study, it is found that if the local municipality is planning to abandon landfill disposal method, it is critically important to excluding the plastic wastes from MSW incineration on account of a considerably large portion of GHG emission is discharged from plastic incineration. However, given that the clinkers from MSW incineration are still needed to be treated in landfills, and less GHG emissions are released by the landfill of residual MSW compared with incineration, disposing of MSW in landfills with landfill gas collection facility in another city still can be an appropriate option, but it is vital to maintain the high landfill gas collection efficiency when planning to do so, and extra transport distance would only result in a quite small amount of GHG. Otherwise, composting can be also a good choice, for mitigating the GHG emissions of local MSW management system. More importantly, when planning MSW incineration, the electricity production efficiency can impose significant influence on GHG mitigation, thus it is necessary to improve the installed electricity generation capacity and energy recovery efficiency. Despite the GHG emissions of MSW transfer and transport can be negligible, 8% GHG emission can be reduced when substituting liquefied natural gas for the diesel fuel, and waste transfer stations are no longer needed if the source the source-separated collection can be successfully implemented. Besides, since there is only one type of recyclable waste collection bin available in the city, further segregation for collected recyclables are demanded before being recycled, which results in unnecessary extra GHG emissions. Therefore, the local municipality could consider installing more further-classified recyclable waste bins specific for each type of recyclable wastes in communities and public areas, which can not only provide supports to MSW recycling but also contribute to GHG mitigation. In this manner, the GHG emissions of the MSW management system can be reduced as much as possible if the aforementioned details can be given attention.

As MSW recycling can be fairly complex in reality, the evaluation of MSW recycling becomes the main limitation of this study. Hence, the MSW recycling study could be the topic for future research specifically focused on the Chengdu region.

Eventually, based on the results of this study, several recommendations are put forward for the local municipality with regard to MSW management:

(1) Keep stimulating the source-separated collection;
(2) Optimizing the strategies and infrastructures for MSW transport, transfer, and collection;
(3) Handling each MSW components with proper treatment approaches;
(4) Considering to locate landfills in another region or to expand the processing capacity of composting plant;
(5) Maximizing the recycling rate of MSW

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