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Life cycle assessment of municipal solid waste management with regard to greenhouse gas emissions: Case study of Tianjin, China

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ABSTRACT

The environmental impacts of municipal solid waste (MSW) management have been highlighted in China, due to the continually increasing amount of MSW being generated and the limited capacity of waste treatment facilities. Of particular interest is greenhouse gas (GHG) mitigation, aided by the Kyoto Mechanisms. China is an important case study for this global issue; however, an analysis of the entire life cycle of MSW management on GHG emissions is not available for China. This study evaluates the current and possible patterns of MSW management with regard to GHG emissions, using life cycle assessment (LCA), based on the Tianjin case. We assess the baseline scenario, reflecting the existing MSW management system, as well as a set of alternative scenarios, five exploring waste treatment technology innovations and one exploring integrated MSW management, to quantitatively predict potentials of GHG mitigation for Tianjin. Additionally, a sensitivity analysis is used to investigate the influence of landfill gas (LFG) collection efficiency, recycling rate and methodological choice, especially allocation, on the outcomes. The results show GHG emissions from Tianjin's MSW management system amount to 467.34 Mg CO_2 eq. per year, based on the treatment of MSW collected in the central districts in 2006, and the key issue is LFG released. The integrated MSW management scenario, combining different improvement options, shows the highest GHG mitigation potential. Given the limited financial support and the current waste management practice in Tianjin, LFG utilization scenario would be the preferred choice. The sensitivity analysis of recycling rate shows an approximately linear relation of inverse proportion between recycling rate and total GHG emissions. Kitchen waste composting makes a considerable contribution to total GHG emissions reduction. Allocation choices result in differences in total quantitative outcomes, but preference orders and contributions analysis are found to be robust, suggesting LCA can support decision making.

1. Introduction

Municipal solid waste (MSW) management in China has emerged as a serious issue, which poses a challenge with regard to environmental quality and sustainable development. Cities are confronted with unprecedented stresses from inefficient MSW management, such as the lack of MSW treatment capacity and improper technologies being employed, resulting in environmental degradation. Of particular interest are greenhouse gas (GHG) emissions from waste management, which have been

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evaluated in a new separate chapter contributing to the IPCC's Fourth Assessment Report (Bogner et al., 2007). China is an important case for this global issue, because of its continually increasing MSW generation, which has been estimated to show an average annual growth rate of 8–10% (Cheng et al., 2007). At the same time, the carbon exchange scheme, aided by the Clean Development Mechanism (CDM), provides a more economically efficient way to meet the Kyoto targets: reducing costs of obligated parties and transferring funds to developing countries (Barton et al., 2008). Thus, assessing the impact of current and potential patterns of waste management on GHG emissions is essential, if China is to benefit from CDM projects and improve its waste management practices.

Case studies on environmental performances, especially with regard to GHG emissions, of various waste management strategies have been implemented for most developed countries and some developing countries (Weitz et al., 2002; Mendes et al., 2004; Liamsanguan and Gheewala, 2008). Life cycle assessment (LCA) has been acknowledged as a tool enabling researchers to consider the full life cycle of MSW management system, and the holistic information provided by it has been used for decision support in MSW management planning. However, the results of these studies are difficult to generalize, because waste characteristics and technology choices are highly dependent on the local situation. Compared to developed countries, MSW in China, as in many developing countries, has two primary features. One is the high organic waste content, which significantly affects the GHG emissions from the MSW management system. The other is the high moisture content, which directly affects the choice of waste strategy and the corresponding GHG emissions. This article extends the research into a specific area, viz. the influence of MSW management on GHG emissions in China, using Tianjin as a case study. Furthermore, it explores the influence of methodological choices, especially allocation, on the outcomes. The most popular method used in previous studies to solve the problems relating to multifunction and allocation, is system expansion or substitution. However, as pointed out by Winkler (2004), this allocation methodology leads to diverging and even conflicting results, which would restrict the usefulness of LCA as a policy supporting tool. There is therefore a need for a more transparent LCA study of MSW management with respect to allocation methodologies.

In the present study, an LCA of MSW management is conducted with an impact assessment limited to GHG emissions. The study analyzed the full life cycle of MSW management, including collection and transport, waste treatments, infrastructure for waste treatment facilities, and production of energy and ancillary materials consumed. LCA is used as an evaluation tool, following the ISO standard (ISO, 2006). We describe the GHG emissions from the current Tianjin MSW management system to highlight the critical issues. In addition to this baseline scenario, we compare another six scenarios reflecting different MSW management strategies, to assess the potential for GHG emissions mitigation and trade-offs. A contribution analysis and a sensitivity analysis on landfill gas (LFG) collection efficiency, recycling rate, and allocation method are undertaken to support the LCA results.

Tianjin City is selected as the location for a case study. It is situated 120 km southeast of Beijing and is one of the four municipalities directly under the Central Government, with an urban area of 11,920 km^2 and 10.75 million inhabitants. Tianjin's GDP has grown at an annual rate of 13.9% over the past five years, and the annual per capita GDP was 40,350 CNY (approximate 5117 US$) in 2006 (TBS, 2007), the fifth highest in China. MSW is being generated at a rate of approximately 4500 tons a day. Of the generated waste, 85% is subject to waste treatment while 15% is littered or recycled informally. Landfill and incineration are the main disposal routes in Tianjin's MSW management system.

2. Methods and data

2.1. *Goal and scope definition*

The goal of this study is two-fold: to evaluate GHG emissions of the existing MSW management system in Tianjin from a life cycle perspective; and to investigate the potentials of GHG emissions mitigation and trade-offs under different MSW management strategies through scenario studies.

2.1.1. *Functional unit*

The functional unit in this study is defined as "the disposal of the MSW collected by the central districts of Tianjin city in 2006". MSW, referring to the waste discarded in urban areas, is mainly household and retailer waste, but also includes small amounts of industrial and construction wastes mixed in occasionally. The total amount is 909,160 tons (55% of the MSW generated in whole Tianjin City), of which fraction composition and elementary composition have been analyzed (TCAEEDRI, 2007a), as shown in Table 1, where the percentage

Table 1 – Fraction composition and elementary composition of MSW in Tianjin

Fraction	Amount	Moisture	C	H	O	N	S	Ash
	ton	%	%	%	%	%	%	%
Kitchen waste	517,130	70	48(100)	6.4	37.6	2.6	0.4	5
Slag and ceramics	147,375	20	24.3(0)	3	4	0.5	0.2	68
Metals	3818	2	4.5(0)	0.6	4.3	0.1	0	90.5
Glass	11,820	2	0.5(0)	0.1	0.4	0.1	0	98.9
Paper	78,824	10.2	43.4(100)	5.8	44.3	0.3	0.2	6
Plastics	110,190	1.2	60(0)	7.2	22.8	0	0	10
Textiles	22,456	10	48(80)	6.4	40	2.2	0.2	3.2
Wood	17,547	1.3	49.6(100)	6	42.6	0.2	0.1	1.5
Total/average	909,160	44.39	44.45(64)	5.78	30.47	1.65	0.28	17.37

of biogenic carbon is bracketed in the fourth column. The lower heating value and moisture contents of the MSW in Tianjin are 5176 kJ/kg and 44.39%, respectively. A closer look at the slag & ceramics item, which is a specific component of MSW in China, shows that its share in the total MSW varies with the seasons (1.58% in summer and 35.89% in winter) (TCAEEDRI, 2007a). It is reasonable to assume that this item mostly comprises residues from individual heating systems, while the amount of ceramics is relatively small.

2.1.2. *Scenarios*

This study compares seven scenarios, reflecting different MSW management systems. The scenarios are assumed not to influence MSW generation, so the same amounts of MSW with the same composition, are disposed of in all scenarios.

- S0 Baseline. S0 corresponds to the current MSW management system in the central district of Tianjin. According to Tianjin statistical data for 2006 (TCAEEDRI, 2007b), 48.9% of MSW was treated in a MSW-to-energy plant, 49.5% was disposed of in monitored landfills without LFG utilization, and the rest was open dumped due to lack of treatment capacity. Source separation has not been introduced into the existing system.
- S1 LFG utilization. Compared to S0, the landfill plant in this scenario is equipped with LFG collection, upgrade, and conversion system. LFG is assumed to produce electricity.
- S2 Incineration. All of the MSW is assumed to be treated in the MSW-to-energy plant. This scenario tests the benefit from incineration with energy recovery instead of LFG utilization.
- S3 Materials recycling. This scenario aims to explore the potential to reduce GHG emissions by materials recycling. Mixed metals, glass, paper, and plastics are assumed to be treated in a material recycle facility (MRF), producing secondary materials. As shown in Table 1, the proportions of some recyclable fractions in the total MSW are relatively small, such as glass 1.3%, metals 0.42%, and paper 8.67%. This is the result of scavenging activities, which exist in nearly every stage of Tianjin's MSW management, from generation to final disposal.[1] In the absence of data on recycling mixed waste, a simplified rate of 30% is assumed from average data provided by USEPA (Thorneloe et al., 2007). The same amount of MSW, with the same composition as in S0, is treated in the MSW-to-energy plant.[2] The remaining MSW is landfilled, without LFG utilization.
- S4 Centralized composting. The design of this scenario is based on Tianjin's waste management proposal. Fifty percent of kitchen waste is assumed to be separated at source and collected to be composted. The digested matter is assumed to be used as fertilizer. The same amount of MSW, with the same composition as in S0, is transferred to the MSW-to-energy plant. The remaining MSW is assumed to be landfilled without LFG utilization.
- S5 Anaerobic digestion. Different from S4, 50% of kitchen waste is assumed to be treated in an anaerobic digestion (AD) plant. The biogas generated from AD process is assumed to be used for electricity generation, and the digested matter is also used as fertilizer. The treatment choices for the rest waste streams are the same as in S4.
- S6 Integrated system. This scenario investigates the potential to minimize GHG emissions through integrated MSW management system. Metals, glass, paper, and plastics are recycled in the MRF at a 30% rate, and 50% of kitchen waste is separated at the source and collected to be treated by AD. The same amount of MSW, with the same composition as in S0, is transferred to the MSW-to-energy plant. The remaining MSW is treated in landfill with LFG utilization.

2.1.3. *System boundary*

The relevant processes are included within the boundary of MSW management system, as shown in Fig. 1. MSW is the input of the MSW management system. Upstream processes related to the manufacture and use of products entering the waste stage, are excluded. A foreground system and a background system are defined to distinguish between direct and indirect burdens. The foreground system of which the specific data are acquired, is directly related to waste treatment processes, including collection and transportation, MSW-to-energy, composting, AD, MRF and landfill with or without LFG utilization. The production of energy and materials are included in the background system. When substitution is used as the allocation method, the system boundary is expanded and avoided processes are included in the system, as enclosed by the dashed line in Fig. 1.

2.2. *Inventory*

The life cycle inventory (LCI) aims at identifying and quantifying the environmental interventions related to the system, and results in a list of environmental inputs and outputs.

2.2.1. *Key assumptions*

In the LCI phase, key assumptions of this study are the following:

- Short-cycle biogenic CO_2 emissions are considered to be "carbon-neutral", i.e. not contributing to global warming, and are therefore omitted from the inventory. Biogenic C released as CH_4 however is included.
- The MSW-to-energy plant and landfill plant are located at the edge of the central district of Tianjin city. The average collection and transport distance to the MSW-to-energy plant and the landfill plant is assumed to be 20 km (both ways). MRF, composting and AD plants are assumed to be constructed in the periphery of the central district, with a distance of 30 km (both ways).
- As GHG, CO_2, N_2O, and CH_4 are included. Other GHG are hardly emitted from the MSW management system and therefore ignored.

[1] In fact, this scavenging is also a recycling activity. Because quantitative data are not available, this has not been included in the scenario.

[2] This assumption may simplify the reality. The MSW composition may be changed, which is decided by the whole MSW management scheme. Also seen in S4, S5, and S6.

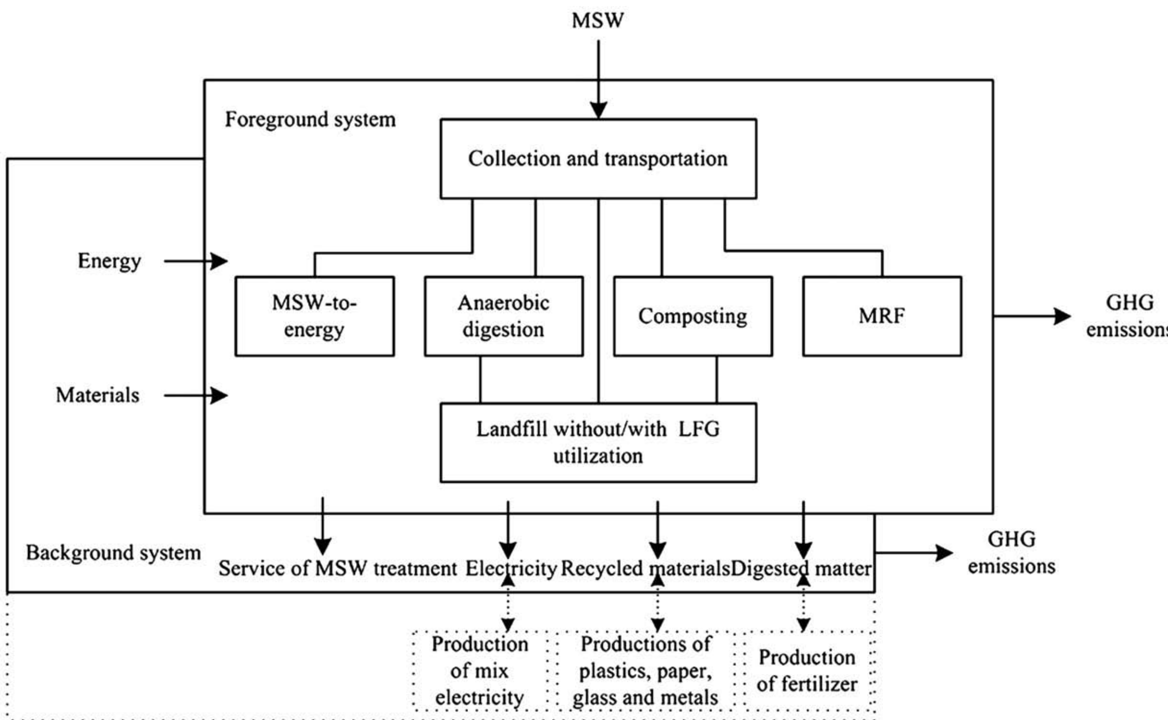

Fig. 1 – System definition and system boundary.

2.2.2. *Data issues*

The data used in this study were derived from on-site investigations and other databases. Data on MSW-to-energy and landfill without LGF utilization were obtained from reports by the Tianjin MSW-to-energy plant (2006) and the Tianjin Shuanggang landfill plant (1999). Since specific data on MRF, composting and AD are not available for Tianjin's MSW management system, the relevant data were obtained from the Ecoinvent database (Ecoinvent Center, 2007). Data on collection and transport were calculated from Tianjin statistical data (TCAEEDRI, 2007b). As for the emissions from electricity production required to feed the system, the 2002 Chinese electricity supply mix (75.9% coal, 3% oil, 2% natural gas, 17.6% hydropower, and 1.5% nuclear power) was taken from the literatures (NBSC, 2003; Di et al., 2007). Other relevant data on the processes in the background system were based on the Ecoinvent database.

2.2.2.1. *MSW-to-energy*. The Tianjin MSW-to-energy plant, equipped with three incineration lines and two sets of steam turbine electricity generators, was put into full operation in July 2004. Currently, the plant incinerates 1200 tons of MSW per day, approximately one third of the total MSW generated in Tianjin. Each incineration line consists of a 400 ton per day grate incinerator, a boiler, a semi-dry scrubber, an active carbon ejector, and a fabric filter system. The average MSW input has a lower heating value of 5176 kJ/kg, and according to the annual report by the Tianjin MSW-to-energy plant (2006), it can generate 1.23E8 kWh net electricity per year. The bottom ash and fly ash are disposed of in a sanitary landfill. CO_2 emission data is the average of on site monitoring data, of which frequency is once per hour. N_2O and CH_4 emissions are not monitored continuously, and the relevant data were from sample tests, of which frequency is four times per year. Emission factors (Doka, 2003) were used to calculate the ratio of biogenic CO_2 to biogenic CH_4. The most relevant energy and ancillary materials included in the LCI are diesel for ignition and supplementary fuel, CaO and activated carbon for flue gas cleaning, and HCl and NaOH for water treatment. The capital equipments and infrastructure data on the MSW-to-energy plant were derived from the Ecoinvent database.

2.2.2.2. *Landfill*. Landfill without LFG utilization is the current choice for landfill technology in Tianjin. In this study, the data from the Tianjin Shuanggang landfill plant (1999), which has been running for 7 years at a capacity of 2700 ton per day, were used to calculate (1) energy and ancillary material consumption, including electricity, diesel for the compactor and the scraper, and NaOH, CaO and HCl for leachate treatment; and (2) landfill plant infrastructure and equipments, including major building materials such as HDPE layer, steel, clay, and cement. The volumes and composition of LFG in the short term (100 years) were estimated using transfer coefficients (Doka, 2003). In Tianjin's current situation, LFG is released directly into the atmosphere. In the landfill with LFG utilization scenario, 50% of LFG is assumed to be captured and converted into electricity at 30% efficiency. For open dump, emission coefficients are assumed to be the same as those used for landfill without LGF utilization.

2.2.2.3. *Materials recycling*. Waste paper, glass, metals, and plastics are assumed to be sorted at the MRF, and treated by different recycling processes. Modelled materials recycling processes were mainly derived from the Ecoinvent database, as listed in Table 2. The recycling LCI data on waste plastics, which was assumed to be composed of 75% PET and 25% PE, were acquired from Arena et al. (2003).

2.2.2.4. *Composting and AD.* Kitchen waste, separated at source, is assumed to be delivered to a central composting plant or a central AD plant. Energy consumption and gas emissions of composting and AD were derived from the Ecoinvent database. The nutrient contents of digested matters is assumed 0.0083 kg N and 0.002 kg P per kg digested matter for composting process, and 0.0076 kg N and 0.0011 kg P per kg digested matter for AD process (Finnveden et al., 2000).

2.2.2.5. *Collection and transport.* Waste collection and transport in Tianjin is carried out by diesel-fuelled lorries which pick up the MSW from households or roadsides and deliver it to transfer stations or waste treatment facilities. A type of 5 ton diesel lorry is assumed for Tianjin's MSW management system, with a load factor of 0.7 according to Tianjin statistical data (TCAEEDRI, 2007b). Diesel consumption and emission factors for a 5 ton lorry were estimated at 0.238 kg/ton km, CO_2 0.75 kg/ton km, CH_4 4.22E–5 kg/ton km, and N_2O 1.92E–5 kg/ton km, based on data from the Chinese energy statistical yearbook (NBSC, 2006).

2.2.3. *Allocation*

The allocation procedure in a multi-functional process is a critical issue in LCA studies, especially in those on waste management systems. Waste treatment systems are becoming increasingly complex and multi-functional, as technical innovation progresses. The ISO standard for LCA (ISO, 2006) describes acceptable allocation procedures in the following order of preference: (1) avoiding allocation by dividing processes into sub-processes; (2) avoiding allocation by expanding the system; (3) applying principles of physical causality for allocation burdens; and (4) applying other principles of causality, for instance economic value. The system expansion or substitution option dominates LCA studies of waste management systems. Heijungs and Guinée (2007) analyzed the problems of these two options and state a preference for economic partitioning based on both theoretical and practical points of view. As the allocation method has a large influence on results, the robustness and the usefulness of LCA results for decision support could be limited. In order to investigate the diversity of results related to GHG emissions from MSW management system as a result of allocation choices, this study consistently applies two approaches: economic partitioning and substitution.

Table 2 – Substitution options

Item	Recycling processes	Avoided processes	Replacement ratio
Electricity	MSW-to-energy and LFG utilization	Chinese electricity supply mix	1:1
Digested	Compost, at plant CH	N: ammonium nitrate, as N, at regional storehouse RER	1:1
matter	Biowaste, to anaerobic digestion CH	P: diammonium phosphate, as P_2O_5, at regional storehouse RER	1:1
Paper	Paper, recycling, no deinking, at plant RER	Paper, newsprint, 0% DIP, at plant RER	1:1
Glass	Glass, cullets, sorted, at sorting plant RER	Packaging glass, brown, at plant RER	1:0.2
Metals	Steel, electric, low-alloyed, at plant RER	Steel, converter, low-alloyed, at plant RER	1:1
Plastics	Plastics recycling, at the specific plant	PET: polyethylene terephthalate, granulate, bottle grade, at plant RER	1:0.98
		PE: polyethylene, LDPE, granulate, at plant RER	1:1

2.2.3.1. *Economic partitioning.* Economic partitioning was conducted as the baseline allocation method in this study for scenario studies, based on the conclusions drawn by Heijungs and Guinée (2007). Economic partitioning was performed on the basis of the economic value of the various products or services produced by the system, which was calculated as quantity times price. Tianjin's municipal administration is in charge of MSW management, including investment and operation. The disposal fees (also called tipping fees) account for about a third of revenues, while the remaining revenues are derived from subsidies and general government budgets (World Bank, 2005). The expenditures of MSW-to-energy and landfill currently are 167 CNY/ton and 40 CNY/ton, respectively. The prices of composting and MRF were assumed to be 50 CNY/ton and 100 CNY/ton respectively, based on the waste treatment policy stimulated by the government (TCAEEDI, 2007). The price of AD is considered as the same as that of MRF. The price of electricity recovered from the MSW treatment is 0.3 CNY/kWh. Prices for the recycled materials are 1000 CNY/ton for paper, 300 CNY/ton for glass, 1500 CNY/ton for metals, and 4000 CNY/ton for plastics (Tian et al., 2007). Digested matter generated from composting and AD is usually distributed among the farmers free of charge, based on the experience gained in European countries. Consequently, no environmental burdens were allocated to the production of the digested matter. Table 3 lists the economic allocation factors for different waste treatment processes.

2.2.3.2. *Substitution.* The starting point for the substitution method is that the system delivers co-products in addition to its main service, viz. waste treatment. This avoids the need to produce these co-products separately by the "normal means of production". These avoided processes can therefore be subtracted from the MSW management system. In this case, Chinese electricity production in 2002 was chosen as the avoided process for the electricity recovered from MSW treatment. When recycled materials are assumed to replace virgin materials, choices have to be made regarding avoided processes. Although many recycled materials have an equivalent amount of virgin materials, the replacement ratio, defined as recycled material:virgin material, is in some cases less than

Table 3 – Allocation factors for economic partitioning

Process	Function							
	Service of waste treatment	Recovered electricity	Digested matter	Recycled paper	Recycled glass	Recycled metals	Recycled PE	Recycled PP
MSW-to-energy	0.62	0.38						
Landfill with LFG utilization	0.74	0.26						
Composting	1		0					
Anaerobic digestion	0.82	0.18	0					
Paper recycling	0.11			0.89				
Glass recycling	0.16				0.84			
Metals recycling	0.06					0.94		
Plastics recycling	0.04						0.69	0.27

1:1 (Bjorklund and Finnveden, 2007), shown in Table 2. Since data on 100% virgin glass production as available, a hypothetical replacement ratio of 1:0.2 was estimated, based on the flat glass production process in China, in which 200 g of recycled glass is inputted for 1 kg of flat glass produced (Chen et al., 2006). In cases of composting and AD, the digested matter was assumed to replace industrial fertilizer in a 1:1 ratio.

2.3. *Impact assessment and interpretation*

This study focuses on global warming as the only impact category, using the global warming potential for a 100-year time horizon (GWP100) as its characterization factor.

The interpretation of the results is supported by contribution and sensitivity analyses. The computations followed the method developed by Heijungs and Kleijn (2001). Through the contribution analysis identifies those processes or elements that make the highest contribution to a certain emission or category, allowing the key problems or improvement potentials in the case study to be pinpointed. The sensitivity analysis identifies sensitive parameters, i.e. whether a small change in an input parameter would induce a large change in the impact category. Here, the input parameters for sensitivity analyses focus on the LFG collection efficiency and the recycling rate. The sensitivity analysis also tested the effects on LCA results of the different allocation method choices. These two analyses were performed at the level of characterization.

3. Results and discussion

Results of seven scenario studies were computed by means of the CMLCA (Chain Management by Life Cycle Assessment) software package (CML, 2004). As mentioned above, economic partitioning was chosen as the baseline allocation method for scenario studies in this case. Therefore, results of the impact assessment, contribution analysis and the sensitivity analyses on the LFG collection efficiency and the recycling rate are discussed under this assumption.

3.1. *Impact assessment and contribution analysis*

Fig. 2(a) presents the results of the scenario calculations, and also identifies dominant processes contributing to total GHG emissions. Based on the total GHG emissions, a preference ranking of the scenarios can be indicated. S6 combining all GHG reduction options, appears as the best waste management option, as was to be expected. In S6, GHG emissions are reduced by approximately 40% compared to the baseline scenario. S1 approaches S6 and is better than S2, which in turn is better than S4 and S5. S0 does not differ much from S3 and is the least preferable option. The waste treatment processes themselves, including landfill, incineration and recycling, are important for GHG emissions, while other parts of the life cycle, such as collection and transport, infrastructure, ancillary materials production, and energy consumption, have a negligible influence. Below, a more in-depth discussion about each scenario is presented.

3.1.1. *S0 baseline*

The results for S0 indicate that GHG emissions from the current MSW management system are 467.34 Mg CO_2 eq., based on MSW collected in the central districts of Tianjin in 2006. As shown in Fig. 2(a), the landfill and incineration contribute about 68% and 26% to total GHG emissions, respectively. The landfill process in S0 is not equipped with LFG collection and flaring systems, which results in GHG emissions of 0.65 kg CO_2 eq. per kg waste. The most important issue for this the CH_4 release at landfill sites, due to organic waste degradation. The MSW treated in MSW-to-energy produces 0.53 kg CO_2 eq. per kg waste, which mainly comes from the oxidation of the fossil carbon content of MSW. Plastics waste is the main source of fossil carbon, as shown in Table 1. Since electricity is generated as a co-product, a proportion of the GHG emissions are allocated to it, resulting in net GHG emissions of 0.33 kg CO_2 eq. per kg waste for the waste treatment service. The contribution analysis for the present MSW management in Tianjin shows that the direct LFG released from landfill is the key issue for global warming, indicating a high potential for GHG emissions mitigation.

3.1.2. *S1 LFG utilization*

This scenario tests the effect of LFG utilization in the form of electricity. The total GHG emissions from this scenario are 39% lower then those in S0. The MSW treated in landfill with energy recovery produces a gross amount of 0.35 kg CO_2 eq. per kg waste, of which 0.26 kg CO_2 eq. per kg waste is allocated to the waste treatment service. Although the landfill process is

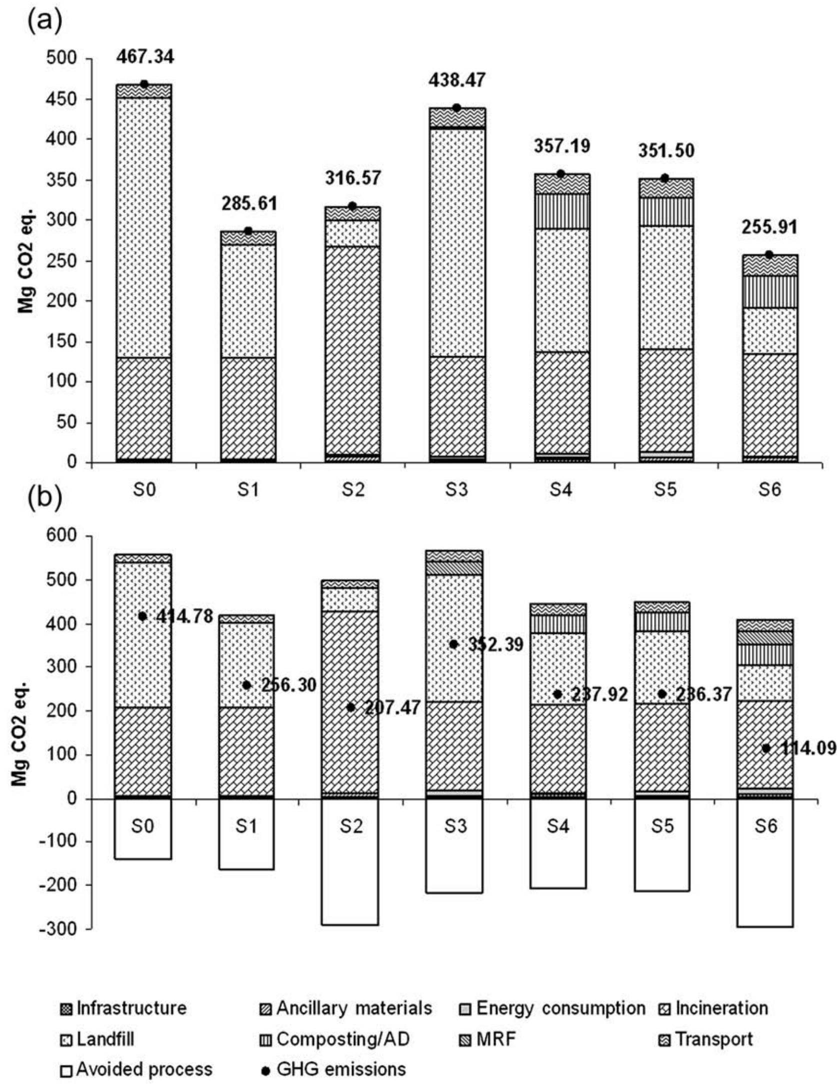

Fig. 2 – Contributions of main stages to GHG emissions with allocations of (a) economic partitioning and (b) substitution.

still the major contributor in the MSW management system, a significant benefit can be achieved when introducing the direct LFG recovery technology.

3.1.3. *S2 Incineration*

In this scenario, MSW-to-energy appears to reduce GHG emissions by 32% compared to S0. S2, however, shows no advantage compared to S1. The choice of allocation, economic partitioning, mainly causes the preference for the LFG utilization scenario, compared to the incineration scenario. Based on the gross GHG emissions from MSW-to-energy and landfill with LFG utilization processes and the allocation factors, more GHG emissions are allocated to the waste treatment service in MSW-to-energy than that in landfill with LFG utilization. In the present study, 0.33 kg CO_2 eq. per kg waste is for MSW-to-energy, and 0.26 kg CO_2 eq. per kg waste is for landfill with LFG utilization.

3.1.4. *S3 Materials recycling*

The amount of GHG emissions from S3 is only slightly lower than that from S0, and higher than those from S1 and S2. Because of the small amounts of recyclable fractions in Tianjin's MSW, the MRF has an insignificant effect on improving GHG emissions from the whole MSW management system. The increased effort required for waste collection and the larger transport distances increase GHG emissions even further in S3.

3.1.5. *S4 Composting and S5 AD*

Compared to S0, S4 and S5 yield 24% and 25% reduction of GHG emissions, respectively. Since a large part of Tianjin's MSW is kitchen waste (see Table 1), it is worth noting that there is a significant potential for GHG emissions mitigation, if kitchen waste is efficiently source-separated and not landfilled. GHG emissions from S4 and S5 are almost the same, which indicates that there is no significant difference between these two technical alternatives, in terms of global warming. N_2O formation in the composting process contributes 10% to total GHG emissions. Compared to S4, S5 consumes more external energy; on the other hand, it produces electricity from biogas. The net effect of these two mechanisms is almost zero.

3.1.6. S6 Integrated system

With the purpose of testing a combination of options in an integrated MSW management system, this scenario generates the lowest GHG emissions, approximately half of those in baseline scenario. In practical terms, however, this choice may not be feasible. It requires the introduction of three technologies, LFG utilization, MRF and AD, into the current system, which would involve high capital investments and complex operations; whereas only LFG utilization or AD will also reduce GHG emissions significantly. If the system boundary is extended to encompass the scavenged materials, more recyclable fractions flow into MRF, and the efficiency of the integrated MSW management would probably increase. The same may be true if other impact categories besides global warming are included in the analysis.

3.2. Sensitivity analysis

3.2.1. Sensitivity to allocation method

LCA studies of waste management systems have yielded quite diverging and even conflicting results, due to underlying methodological choices and assumptions. This section examines the consequences of different choices for the allocation method.

Fig. 2(a) and (b) presents total GHG emissions outcomes and contributions of seven scenarios, based on economic partitioning and substitution, respectively. The figures show a general decreasing trend in total GHG emissions for each scenario when shifting from economic partitioning to substitution. The difference in absolute values is significant and also different for each scenario, being largest in S6 and smallest in S1. However, the ranking order of the scenarios is almost the same, except for S1 and S2. The key issues of each scenario, as identified with contribution analysis based on both allocation methods, are also similar.

In the future, a policy to improve the waste management system is expected to be established, based on the experience gained in developed countries. A tax on waste landfill would be introduced, with the purpose of encouraging waste reduction, materials recycling and biological treatment for organic waste. This would raise the economic allocation factor for landfill service and reduce GHG emissions from landfill. Furthermore, the market for compost from waste could be expected to change, resulting in a positive economic value for the digested matter. Consequently, the potentials for GHG emissions mitigation in the scenarios with biologic treatments for kitchen waste can be significantly expanded.

The main cause of the differences between economic partitioning and substitution is that different systems are being modelled. According to the authors' experience, economic partitioning has the advantage of being applicable in most, if not all situations. Its disadvantage is that it changes over time due to market developments. Substitution on the other hand requires more data, and moreover it could be difficult to decide on the avoided processes or the replacement ratio of a substitute compared to the original flow in some cases (e.g., composting), as discussed by Weidema (2001), Heijungs and Guinée (2007).

3.2.2. Sensitivity to LFG collection efficiency

Fig. 3 shows the effect of changing the LFG collection efficiency for S1 and S6, which include LFG utilization process, based on economic partitioning. In S1, from the base case of 50%, increasing LFG collection efficiency by 10% results in decreased GHG emissions by 6.3%; on the other hand, decreasing LFG collection efficiency by 10% results in increased GHG emissions by 5.5%. Compared to S1, the influence of LFG collection efficiency is less significant in S6, due to the smaller amount of MSW going to landfill in S6. Approximately, a 10% change in the LFG collection efficiency results in a 2.5% reduction of total GHG emissions. It is worth noticing that the preference order between S1 and S6 reverses, when a higher LFG collection efficiency assumed. In this case, when the collection efficiency rises above 60%, S1 shows less GHG emissions than S6. Increasing the LFG collection efficiency causes two positive effects: the decrease of GHG emissions from LFG releasing, and the increased electricity production. The high sensitivity of LFG collection efficiency to GHG emissions shown here is consistent with the study by Wanichpongpan and Gheewala (2007). However, it is necessary to point out that the energy demand of LFG utilization process is considered in this study to be invariant to LFG collection efficiency. This assumption, owning to lack of data, could introduce uncertainty in the analysis.

3.2.3. Sensitivity to recycling rate

This section discusses the results of a sensitivity analysis to different recycling rates, ranging from −40% to 40%, on the basis of assumptions in S3 and S6. That indicates the recycling proportions of paper, glass, metals and plastics range from 18% to 42%, and those for kitchen waste rang from 30% to 70%. It is appropriate to test the influence of the recycling rate within these ranges, because the full recycling potential of paper, glass, metals and plastics in Tianjin's MSW cannot be exactly assessed, due to lack of data on scavenging activities; On the other hand, the recycling potential of kitchen waste is higher in Tianjin than in developed countries. Fig. 4 illustrates the sensitivity of GHG emissions to the recycling rate in steps of 20% in S6, based on the economic partitioning.

It is obvious that total GHG emissions from S6 decrease as the recycling rate increases. There is an approximately linear relation of inverse proportion between the recycling rate and GHG emissions, with a coefficient of determination $R^2=0.967$. This linear relation allows the conclusion that, when implementing the integrated MSW management strategy, a 10% change in the overall recycling rates would induce about 0.9%

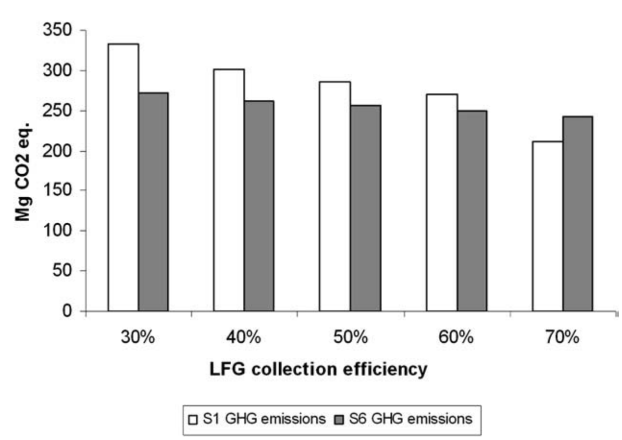

Fig. 3 – Sensitivity to LFG collection efficiency.

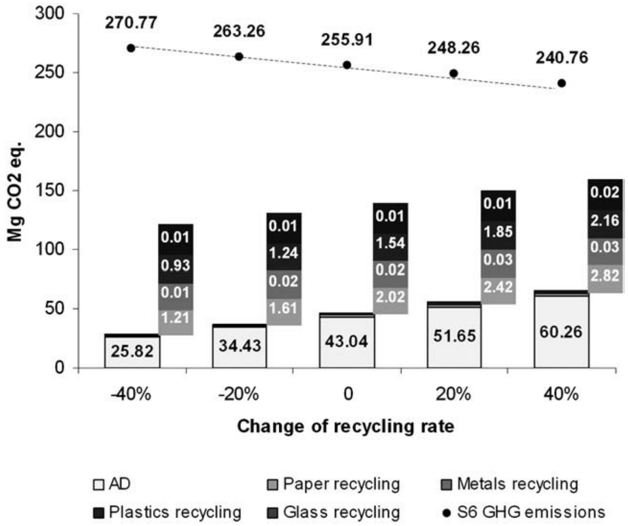

Fig. 4 – Sensitivity to recycling rate.

change in total GHG emissions in the opposite direction. Fig. 4 also shows the sensitivities of GHG emissions to different waste fractions. The high influence of kitchen waste treated by AD on the amount of GHG emissions can be seen. Paper recycling makes a considerable contribution to GHG emissions compared to the other three materials. The high sensitivity to kitchen waste highlights the need for a more accurate inventory analysis and more suitable allocation factors.

4. Conclusions and recommendations

From a life cycle perspective, the current Tianjin's MSW management system emits 467.34 Mg CO_2 eq., based on treatment of the waste collected in the central districts in 2006. The release of LFG from landfill, contributing 68% to total GHG emissions, is a critical issue in the whole MSW management system. The MSW-to-energy plant contributes another 26%; other processes are of minor importance.

Six scenarios were evaluated to explore the potential for GHG emissions mitigation in different MSW management strategies. The results for S1 (landfill with LFG utilization) show that a 39% emission reduction can be achieved by introducing simple and direct LFG recovery technology. S2 (incineration) is also a good option, with slightly higher GHG emissions than S1. Materials recycling yields insignificant effects in terms of improving GHG performance in S3, due to the small shares of recyclable fractions in Tianjin's MSW. No significant difference exists between composting scenario (S4) and anaerobic digestion scenario (S5). Both have a 25% lower GHG emission profile than S0. Compared to the baseline scenario, the integrated scenario S6, combining three options, shows the highest potential (45%) for GHG emissions reduction. The contribution analysis shows that, in each scenario, the waste treatment processes, including landfill, incineration, and recycling, are dominating GHG emissions; while processes such as collection and transport, infrastructure, ancillary materials production, and energy consumption, have a relatively small influence.

The sensitivity analysis for the allocation approach shows that the choice of allocation methodology has a large influence the outcomes of LCA studies. In all scenarios, GHG emissions attributed to the waste management systems are lower if the allocation method is shifted from economic partitioning to substitution. The diverging results produced by different methodologies challenge the application of LCA in the waste management system. However, the ranking orders of the scenarios remain almost the same, and the key issues of each scenario identified by contribution analysis are also similar. The orders of preference, as well as the results of contribution analysis, are therefore rather robust, indicating that the use of LCA to identify promising solutions for GHG reduction in MSW management is appropriate.

The high sensitivity of the LFG collection efficiency to GHG emissions is addressed; therefore, the technical specifications of LFG recovery should be properly assessed and transparently reported. This is especially relevant in the case of developing countries, because of the high organic content in MSW. The sensitivity analysis for the recycling rate reveals an approximately linear relation of inverse proportion between the recycling rate and the GHG emissions from the waste management system. Recycling of kitchen waste makes a significant contribution to GHG emission reduction, compared to the other four materials.

Based on our findings, the preferable MSW management system is the one that integrates LFG utilization, MRF and AD technologies into the existing system. However, given the limited financial support and waste management practice, the first priority to achieve GHG emissions mitigation would be LFG control and utilization. With regard to GHG emissions, kitchen waste recycling by composting or AD seems more appropriate than MRF, assuming that it would be difficult to establish both technologies at the same time.

The present analysis only focuses on GHG emissions, which is just one of the environmental issues related to waste management. In order to build a more complete picture of MSW management, further research should cover broader environmental categories. Some impact categories are expected to show a similar pattern, but for others, especially those related to toxicity, a different picture may emerge. This could also influence the order of preference for waste management options. Besides environmental impacts, costs are of the utmost importance in prioritizing waste treatment options. Hence the present LCA study could be complemented by Life Cycle Costing (LCC), to analyze both aspects within one framework.

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