Waste Management 31 (2011) 793–799

Contents lists available at ScienceDirect

Waste Management

journal homepage: www.elsevier.com/locate/wasman

# Environmental impact assessment of solid waste management in Beijing City, China

Yan Zhao [a,b], Thomas H. Christensen [c], Wenjing Lu [a], Huayong Wu [a], Hongtao Wang [a,*]

[a] Department of Environmental Science and Engineering, Tsinghua University, 100084 Beijing, China
[b] Key Laboratory for Solid Waste Management and Environment Safety, Ministry of Education of China, Tsinghua University, 100084 Beijing, China
[c] Department of Environmental Engineering, Technical University of Denmark, 2800 Kongens Lyngby, Denmark

ARTICLE INFO

*Article history:*
Received 26 July 2010
Accepted 8 November 2010
Available online 9 December 2010

ABSTRACT

The environmental impacts of municipal solid waste management in Beijing City were evaluated using a life-cycle-based model, EASEWASTE, to take into account waste generation, collection, transportation, treatment/disposal technologies, and savings obtained by energy and material recovery. The current system, mainly involving the use of landfills, has manifested significant adverse environmental impacts caused by methane emissions from landfills and many other emissions from transfer stations. A short-term future scenario, where some of the landfills (which soon will reach their capacity because of rising amount of waste in Beijing City) are substituted by incinerators with energy recovery, would not result in significant environmental improvement. This is primarily because of the low calorific value of mixed waste, and it is likely that the incinerators would require significant amounts of auxiliary fuels to support combustion of wet waste. As for the long-term future scenario, efficient source separation of food waste could result in significant environmental improvements, primarily because of increase in calorific value of remaining waste incinerated with energy recovery. Sensitivity analysis emphasized the importance of efficient source separation of food waste, as well as the electricity recovery in incinerators, in order to obtain an environmentally friendly waste management system in Beijing City.



## 1. Introduction

With the rapid economic development and urbanization in countries like China, municipal solid waste (MSW) has rapidly increased and the composition of waste significantly changes, thus causing huge pressure on the environment, human health, and MSW management systems (Wang and Nie, 2001). In Beijing (i.e., Beijing City and the suburbs surrounding it) the daily generated MSW now exceeds 16,000 t, but the daily design capacity of the 17 existing waste treatment and disposal facilities, mainly landfills, is only 10,350 t. Therefore, many of the facilities are overloaded, resulting in the expected closure of nine of the landfill sites in the next few years, which is way ahead of their supposed service lives. This situation requires planning for the establishment of new facilities for waste management. However, identifying which technologies should be used and where these should be located remain under dispute, given the complexity and subjectivity of technology evaluation and selection criteria (Zhao et al., 2007). Therefore, a science-based environmental assessment of realistic and integrated waste management alternatives is useful in the decision-making of future waste management system in Beijing City (Huang et al., 2007).

As the aim of MSW management, apart from removing waste from urban areas, is to reduce or avoid the impacts of MSW on the natural environment and human habitat, the environmental impacts of an entire solid waste management system must be considered when evaluating an existing system and its alternatives (Kirkeby et al., 2006b). The methodology of life cycle assessment (LCA) has recently been investigated and proven to be suited for the environmental impact assessment of MSW system (Arena et al., 2003; Christensen et al., 2007; Kaplan et al., 2009; Rigamonti et al., 2009). Many researchers have conducted studies on life cycle impact assessments of various MSW treatment technologies and systems in various levels and regions (Astrup et al., 2006; Birgisdóttir et al., 2007; Zhao et al., 2009a). Recently, LCA has also been applied in assessing the waste management system in Hangzhou City, China (Zhao et al., 2009b).

This paper investigates the solid waste management system in Beijing City, a typical megalopolis in China, and presents an environmental impact assessment of the MSW system using the LCA model of EASEWASTE for waste management. Environmental impacts to global warming, acidification, photochemical ozone formation, nutrient enrichment and stratospheric ozone depletion from the current waste management scenario (mainly landfills) were modelled. In addition, two future potential waste management scenarios were modelled: a short-term planning scenario focusing on providing sufficient treatment capacity (parts of

* Corresponding author. Tel.: +86 10 6277 3438.
*E-mail address:* htwang@tsinghua.edu.cn (H. Wang).

0956-053X/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.wasman.2010.11.007

landfills are substituted by incinerators), and a long-term planning scenario with additional citizen involvement in source separation and different collection systems (integrated treatment with source separation). The results may be useful in the current discussion and planning of future waste management systems in Beijing City.

## 2. Materials and methods

### *2.1. Waste generation and scope of MSW system in Beijing City*

Beijing is the capital of China and has a population of about 18 million including the surrounding suburbs. The central city, Beijing City alone has about 12 million inhabitants. Focus in this paper is on Beijing City because it faces the most serious situation in terms of providing new facilities for waste management.

Beijing City includes eight districts, covering an area of 1370 km$^2$. According to latest statistical data, approximately 11,798,000 people lived in Beijing City in 2006, corresponding to a population density of approximately 8600 inhabitants per km$^2$. The unit generation rate of waste was 0.96 kg per person per day (any waste separated at the source for recycling by private entrepreneurs is not included). Thus, the total amount of waste generated daily was 11,326 t, which was equal to more than 4 million t per year. The annual generation of waste was applied as basic data in the following environmental impact assessment. The composition of mixed waste was analyzed in 2006, and results showed that water content and lower heating value were 61% and 4560 kJ/kg, respectively. The detailed waste composition, assumed as valid until 2010, is shown in Table 1.

Since the data were collected after source separation of recyclables, the amount of recycled waste was not included in the generation and compositional data. This is the reason why the percentages of metals, glass, and other recyclables in the waste were relatively low. Hence, material recycling is not considered in this study, as majority of the recyclables are managed by other systems. The geographical scope of the waste management system is shown in Fig. 1. Facilities outside the city partly serve the residents in the suburbs.

### *2.2. Collection, transportation, and treatment technologies*

Waste collection and transportation were modelled in terms of diesel consumption, because this is believed to be the main environmental load, and the data were collected from Beijing City. Collection was modelled by trucks with an average fuel consumption of 1.28 L diesel per ton of waste. The fuel consumption of the transporting trucks was 0.128 and 0.080 L of diesel per ton of waste per km from collection to transfer stations and from transfer station to treatment/disposal facilities, respectively. The air emissions of all

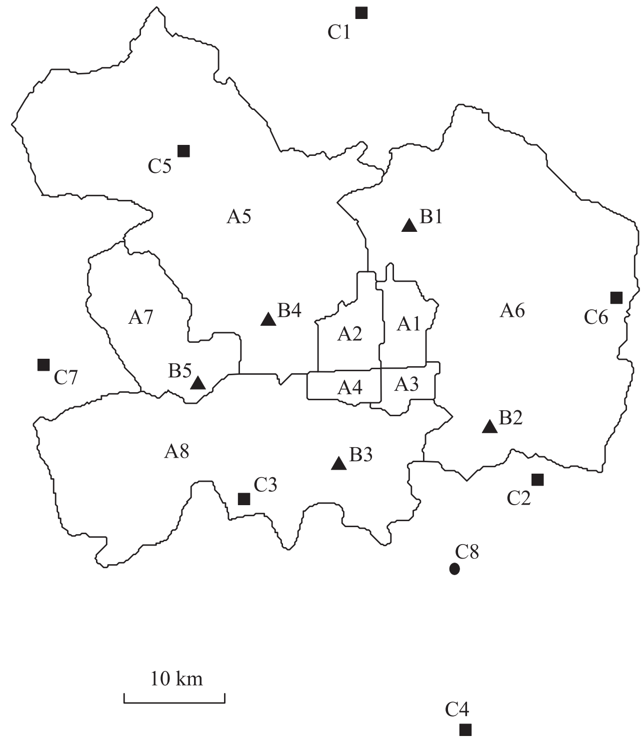


**Fig. 1.** MSW management facilities in the eight districts (A1–A8) of Beijing City. B1–B5: large transfer stations (▲); C1–C8: treatment/disposal facilities (landfill: ■; composting plant: ●).

the trucks were in accordance with Euro III emission standards (Larsen et al., 2009). Transport distances were estimated according to the locations of the facilities.

The main waste management technology used in the MSW system in Beijing City is landfill. Nonetheless, composting is also employed (3–4% of the waste). The general information on the landfills was provided by landfill operators. On-site data, including composition and treatment of gas and leachate, were mainly collected from fields. In landfills, 70% of the gas generated was assumed collected during the first five years and used for electricity production (with an energy recovery efficiency of 30%), while the rest was believed to be flared or vented. Of the leachate, 95% was assumed collected during the first 25 years and treated in wastewater treatment plants. Incineration (future scenarios) was based on grate furnaces equipped with flue gas cleaning (for the main air emission factors, see Table 2) and energy recovery (i.e., 23% electricity and 45% heat recovered based on lower heating values). The recovered electricity and heat substituted the ones

**Table 1**
Composition of MSW in Beijing City.

| Fractions | Percentage by wet weight (%) | TS (%) | Element percentage by weight (%TS) | | | | |
|---|---|---|---|---|---|---|---|
| | | | C | H | O | N | S |
| Vegetable food waste | 63.4 | 17.0 | 48.0 | 6.4 | 38.0 | 2.6 | 0.4 |
| Plastics | 12.7 | 81.6 | 71.0 | 9.7 | 11.1 | 0.5 | 0.05 |
| Paper and cardboard | 11.1 | 70.0 | 44.0 | 5.9 | 44.6 | 0.3 | 0.2 |
| Ash and dust | 6.6 | 84.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Textiles | 2.5 | 84.0 | 55.0 | 6.6 | 31.2 | 4.6 | 0.15 |
| Yard waste, flowers | 1.8 | 34.0 | 47.8 | 6.0 | 38.0 | 3.4 | 0.3 |
| Glass | 1.6 | 84.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.05 |
| Aluminium and other metals | 0.3 | 84.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.01 |
| Total | 100 | 38.8 | 44.8 | 6.0 | 24.7 | 1.2 | 0.2 |

**Table 2**
Information of the main air emissions in incinerators (kg/ton) (Li et al., 2007).

| Air emission | Amount |
|---|---|
| Arsenic (As) | $3.54 \times 10^{-9}$ |
| Cadmium (Cd) | $3.54 \times 10^{-4}$ |
| Carbon monoxide (CO) | 0.53 |
| Chromium (Cr) | $3.54 \times 10^{-7}$ |
| Hydrocarbon (HC) | 0.27 |
| Hydrogen chloride (HCl) | 0.27 |
| Hydrogen fluoride (HF) | 0.01 |
| Lead (Pb) | $5.66 \times 10^{-3}$ |
| Mercury (Hg) | $7.08 \times 10^{-4}$ |
| Nitrogen oxide ($NO_x$) | 1.42 |
| Sulphur dioxide ($SO_2$) | 0.92 |

generated from coal combustion. The detailed information of the incineration technology presumed has been described in our previous work (Zhao et al., 2009b). The composting plant was modelled by standard composting plant (tunnel) available in the EASEWASTE database. It was assumed in all scenarios that the screen rejects from composting and the fly ash from incineration were sent to the nearest sanitary and safe landfills, respectively.

### 2.3. Scenarios

Three scenarios, the current scenario (A) and two scenarios representing future possible developments (B and C), were modelled. Scenario A represents the current MSW system in Beijing City, with the complete dominance of landfills. Scenario B represents a short-term plan, but also a controversial plan, wherein incinerators are suggested to accommodate the waste, as the landfills no longer have capacity to do such. Since local opposition against incineration is strong, it is assumed that the incinerators will eventually be located in the areas of the current landfills. Scenario C represents a long-term plan wherein food waste is source-separated for biological treatment while remaining waste is incinerated. Additional material recycling was not considered in any of the scenarios, as all valuable recyclables have been removed by private entrepreneurs prior to the public collection of waste.

#### 2.3.1. Scenario A: current MSW system in Beijing City

Under this scenario, most of the generated waste is collected and transported to large transfer stations and then to landfills (64.6%) or to the composting plant (3.5%). The rest of the waste is transported directly to landfills (28.4%) or open dumps (3.5%).

#### 2.3.2. Scenario B: short-term plan for the MSW system in Beijing City

Under this scenario, three incinerators are assumed to substitute three landfills (C2, C3 and C4 in Fig. 1, which will reach their capacity and be out-of-service in few years) with a treatment capacity of 4200 t/d (37.1% of generation). The system for transportation with respect to the transfer stations is similar to that in scenario A, as the incinerators are supposed to be situated near the closed landfills.

#### 2.3.3. Scenario C: long-term plan for the MSW system in Beijing City

Under this scenario, seven landfills (C1–C7 in Fig. 1) are replaced by seven integrated treatment facilities, including a composting plant, an incinerator and a landfill for each facility. It is assumed that 50% of food waste in the mixed waste (31.7%) can be source-separated and transported to the composting plants, while the rest of the waste (68.3%) can be transported to incinerators. Residues from the treatment facilities are sent to landfills. All the compost from food waste is utilized for land use and is assumed to substitute mineral fertilizer.

### 2.4. Sensitivity analysis

Due to the uncertainty of the accuracy of some data utilized in the scenarios mentioned above, as well as their potential influence on the results, sensitivity analysis is normally required to assess how sensitive the overall impact is to specified changes in parameters or processes. In this paper, two integrated scenarios were modelled based on scenario C for sensitivity analysis, in which two crucial parameters were selected as typical examples to present the influence of data changes on assessment results, described as follows:

#### 2.4.1. Scenarios C1a and C1b

The expected sorting efficiency of food waste is a key parameter in scenario C due to its crucial influence on the heating value of the remaining mixed waste transported for incineration. Therefore, the sorting efficiency of food waste was adjusted to 30% and 70% in scenario C1a and scenario C1b, respectively, to allow comparison with the results from scenario C (i.e., the sorting efficiency was 50%).

#### 2.4.2. Scenarios C2a and C2b

Considering the huge potential on impact savings from power recovery, the substitution level of electricity generated from incinerators has been identified as another key parameter in scenario C. The level of substitution of electricity recovered from incineration, which was 23% in scenario C, was set at 17% and 11% in scenarios C2a and C2b, respectively, to allow for sensitivity analysis. Electricity recovery efficiency higher than 23% is considered as irrelevant for incineration for wet waste with a low heating value.

### 2.5. LCA method

EASEWASTE has been described by Kirkeby et al. (2006a) and well documented, and was used in a number of cases within waste management (www.easewaste.dk) (Hansen et al., 2006a; Riber et al., 2008; Manfredi and Christensen, 2009). The EASEWASTE-model calculates environmental impacts as normalized potential impacts utilizing the EDIP 1997 impact assessment method as default (Wenzel et al., 1997). Impacts related to global warming was an exception, as it had been updated according to IPCC 2007 (Fourth Assessment Report). Normalization presents a relative expression of the environmental impact or resource consumption

**Table 3**
Normalized environmental impact potential reference in China and typical contributing substances.

| Environmental impacts | Normalization reference in China | Typical contributing substance | Contribution equivalent of substance |
|---|---|---|---|
| Global warming (GW100) | 8700 kg$CO_2$eq/(per·a) | $CO_2$ | 1 kg $CO_2$eq/kg |
| | | $CH_4$ | 25 kg $CO_2$eq/kg |
| | | C sequestered | −3.67 kg $CO_2$eq/kg |
| Stratospheric ozone depletion (OD) | 0.20 kgCFC-11/(per·a) | CFC-11 | 1 kg CFC-11/kg |
| | | CFC-12 | 0.82 kg CFC-11/kg |
| | | 1,1,1-Trichloroethane | 0.12 kg CFC-11/kg |
| Acidification (AC) | 36 kg$SO_2$eq/(per·a) | $SO_2$ | 1 kg $SO_2$eq/kg |
| | | $NO_x$ | 0.7 kg $SO_2$eq/kg |
| | | $NH_3$ | 1.88 kg $SO_2$eq/kg |
| Nutrient enrichment (NE) | 62 kg$NO_3$eq/(per·a) | $NO_3^-$ | 1 kg $NO_3$eq/kg |
| | | $NH_3$ | 3.64 kg $NO_3$eq/kg |
| | | $NO_x$ | 1.35 kg $NO_3$eq/kg |
| Photochemical ozone formation (POF) | 0.65 kg$C_2H_4$eq/(per·a) | $C_2H_4$ | 1 kg $C_2H_4$eq/kg |
| | | CO | 0.04 kg $C_2H_4$eq/kg |
| | | NMVOC (petrol) | 0.5 kg $C_2H_4$eq/kg |

**Table 4**
Waste flow of MSW system in Beijing City in 2006.

| District | | Generation amount | Large transfer station | | Transfer amount | Transport distance | Treatment/disposal facility | | Treatment/disposal amount |
|---|---|---|---|---|---|---|---|---|---|
| No | Name | t/d | No | Name | t/d | km | No | Name | t/d |
| A1 | Dongcheng | 905 | B1 | Datun | 905 | 22.5 | C1 | Asuwei landfill | 905 |
| A2 | Xicheng | 936 | B1 | Datun | 936 | 22.5 | C1 | Asuwei landfill | 936 |
| A3 | Chongwen | 589 | B2 | Xiaowuji | 589 | 6.0 | C2 | Beishenshu landfill | 589 |
| A4 | Xuanwu | 674 | B3 | Majialou | 674 | 19.0 | C8 | Nangong composting | 400 |
| | | | | | | 40.0 | C4 | Anding lanfill | 274 |
| A5 | Haidian | 2391 | B4 | Wuluju | 2279 | 19.5 | C5 | Liulitun landfill | 2279 |
| | | | Not collected or transported | | | 0.0 | | Open dump | 112 |
| A6 | Chaoyang | 3276 | B2 | Xiaowuji | 1315 | 6.0 | C2 | Beishenshu landfill | 1315 |
| | | | Direct to lanfill | | | 18.5 | C6 | Gaoantun landfill | 1800 |
| | | | Not collected or transported | | | 0.0 | | Open dump | 161 |
| A7 | Shijingshan | 435 | B5 | Yamenkou | 420 | 14.0 | C7 | Jiaojiapo landfill | 420 |
| | | | Not collected or transported | | | 0.0 | | Open dump | 15 |
| A8 | Fengtai | 2120 | B3 | Majialou | 600 | 40.0 | C4 | Anding landfill | 600 |
| | | | Direct to landfill | | | 9.5 | C3 | Yonghezhuang landfill | 1414 |
| | | | Not collected or transported | | | 0.0 | | Open dump | 106 |

compared with that of one average person (i.e., normalization reference), providing a normalized impact potential in the unit of person equivalent (PE) (Hansen et al., 2006b). A positive value of normalized impact potential calculated in EASEWASTE presents a contribution to the impact, and a negative one indicates an avoidance of the impact or resource consumption (Kirkeby et al., 2006b). Normalized environmental impact potentials with reference to China were applied and shown in Table 3 (Li et al., 2007), together with typical contributing substances during waste management. Only five environmental elements are available in the normalization reference in China, including global warming, stratospheric ozone depletion, acidification, nutrient enrichment, and photochemical ozone formation.

## 3. Results and discussion

### 3.1. Transportation and waste flow in the current MSW system

The MSW flow in the eight districts of Beijing City is shown in Table 4. Of the 7717 t/d waste, 68.1% was collected and transported to five large transfer stations and then to treatment or disposal facilities; 28.4% was directly transported to landfills; and the remaining 3.5% was not collected nor transported, but considered managed by open dumping. The flows of compost used in field and composting residue sent to the landfills are not shown in the table.

### 3.2. Environmental impact assessment of the current MSW system

The modelling of the environmental impact potentials of the current MSW system in Beijing City showed that $CH_4$ emission is the most dominant contributor to global warming, with the annual amount of $5.5 \times 10^7$ kg. Air emissions of $CH_4$ and VOC from fuel mostly contribute to photochemical ozone formation at $3.8 \times 10^5$ kg and $5.2 \times 10^4$ kg, respectively ($C_2H_4$ equivalents). Similarly, $NH_3$ released to air contributes the most to acidification, as well as to nutrient enrichment. Dichlorodifluoromethane (CFC 12) is the dominant contributor to stratospheric ozone depletion.

The normalized potential impacts of the current system, according to the normalized environmental impact potential reference of China (Table 3), are presented in Fig. 2, with reference to the eight contributing processes and technologies, including collection, transportation, transfer station, landfill, composting, etc.

Results showed that the landfills contribute the most to the impact potentials of global warming and photochemical ozone formation, mainly due to the methane emission mentioned earlier. However, landfills constitute to impact savings on acidification and nutrient enrichment, given the avoided emissions of $SO_2$ ($-2.4 \times 10^6$ kg) and $NO_x$ ($-1.9 \times 10^6$ kg), which profits from the electricity generation from landfill gas. Moreover, the sequestered carbon in landfills ($-7.5 \times 10^4$ PE), presenting the biological carbon assumed as permanently sequestered in the landfill, provides a major impact saving on global warming. Sequestered carbon was calculated based on the input of biological carbon in the waste to the landfill, from which individual amounts of carbon leaving the landfill for the first 100 years through generated gases and leachate are subtracted. The impacts from all transportation units contribute greatly to photochemical ozone formation, which is due to the air emissions including VOC, CO, and NMVOC from fossil fuel combustion. Transfer stations provide significant potential impacts to nutrient enrichment ($1.2 \times 10^4$ PE), photochemical ozone formation ($3.8 \times 10^4$ PE), global warming ($1.1 \times 10^4$ PE), and acidification ($3.4 \times 10^4$ PE). The reason for this is the big amount of electricity consumption by facilities in large transfer stations.

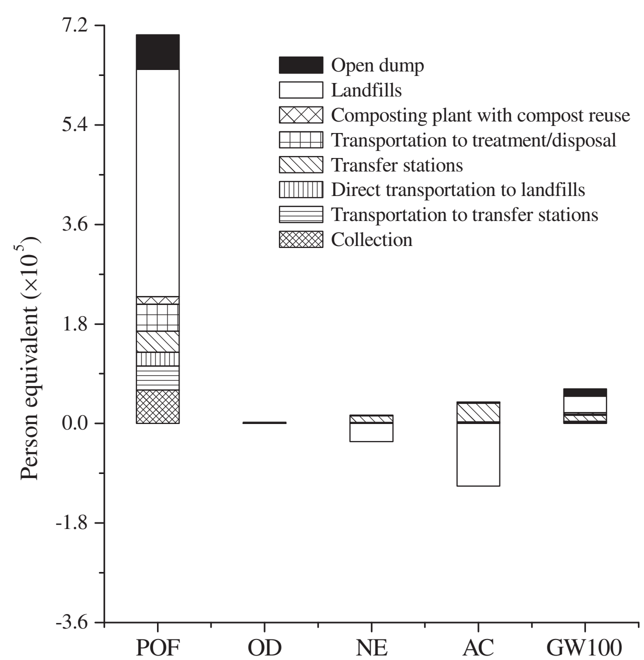


**Fig. 2.** Normalized potential impacts of the current MSW system in Beijing City. POF: photochemical ozone formation; OD: ozone depletion; NE: nutrient enrichment; AC: acidification; GW100: global warming (100 years).

Furthermore, the electricity used in Beijing City is mainly produced from coal combustion and is considered a non-clean energy. The impacts from composting and using compost in land are relatively marginal due to the very small amount. Therefore, methane emission from landfills, long distance transportation, and energy use are key factors in the environmental impact potentials from the current MSW system in Beijing City. These should be paid more attention to when improvement of the system is to be done.

### 3.3. Environmental impacts of scenarios B and C

In scenario B, due to the limited remaining capacity of the facilities, three landfills (C2, C3, and C4) were replaced by three large incinerators in the same locations and with the same treatment capabilities. The normalized potential impacts of scenario B are shown in Fig. 3. The impacts of global warming and photochemical ozone formation are less compared with those seen from the current system (scenario A). This is because reduced waste in landfills results in less methane released. Meanwhile, incineration of mixed MSW can avoid impacts to global warming ($-1.0 \times 10^4$ PE) and photochemical ozone formation ($-1.1 \times 10^5$ PE) through energy recovery. Incineration of mixed waste can also result in impact savings on acidification and nutrient enrichment due to the decrease in $SO_2$, $NO_x$, and HCl emissions resulting from substitution of energy generated from coal. However, the lower heating value of the waste (4560 kJ/kg) is so low that the energy recovered compensates marginally for the emitted fossil $CO_2$. In fact, the lower heating value of the waste is so low that incineration might not occur without the use of auxiliary fuels, such as hard coal (Chen and Christensen, 2010). In these instances, incineration of mixed waste is not considered an appropriate approach to improve the waste management system due to its low benefit to the environment given the low heating value of mixed waste.

In scenario C, the generated mixed waste was separated at source into two fractions, food waste (31.7% of waste generation) and remaining waste (68.3% of waste generation). The former is transported, composted, and then used on land. The latter is transported and combusted to produce electricity and heat. Due to the source separation of food waste, the moisture content of the remaining mixed waste was reduced to 51.1%; consequently, its lower heating value reached 6505 kJ/kg. This was sufficient to support the combustion process (Chen and Christensen, 2010), and thus, no auxiliary fuel was needed, except for furnace activation. Results further showed that incineration of waste after source separation provides a great positive effect to most of the impacts, especially to photochemical ozone formation ($-3.4 \times 10^5$ PE) and acidification ($-2.1 \times 10^5$ PE) (Fig. 4). The avoided impacts in relation to photochemical ozone formation are mainly due to the reduced NMVOC emission, which is a result of the power and heat recovery, and the substitution of fossil fuels like coal and diesel. The avoided environmental impact of acidification is a result of the substitution of coal combustion and the strict air emission control in the incinerators. The avoided impacts to nutrient enrichment and global warming from incineration were $-6.2 \times 10^4$ PE and $-3.5 \times 10^4$ PE, respectively. However, composting was seen to have adverse environmental impacts, especially in terms of its effect to photochemical ozone formation, acidification, and nutrient enrichment. These are mainly due to $CH_4$ emission from the composting facilities as well as the air emissions of $NH_3$ and $SO_2$. However, the compost used as substitute for fertilizer can reduce the impacts to acidification and nutrient enrichment by reducing the pollution and resource consumption from fertilizer production.

The environmental impacts of incineration from scenarios B and C were compared. Incineration of mixed waste can hardly provide benefit to the environment. However, the incineration of waste with much less food waste can avoid a lot of impacts on photochemical ozone formation, nutrient enrichment, acidification, and global warming. This difference is a result of the variations in the heating value of the waste combusted. Based on the calculation in EASEWASTE, the mixed waste sent to incineration in scenario B had a lower heating value of 4560 kJ/kg. This was calculated from the lower heating values for the dry matter of the specific waste fractions, and then corrected for the evaporation of water presence in the wet material fractions. The waste with less food waste in scenario C had a lower heating value of 6505 kJ/kg, much higher than that in the mixed waste in scenario B. This was due to the reduced water percentage resulting from the separation of food

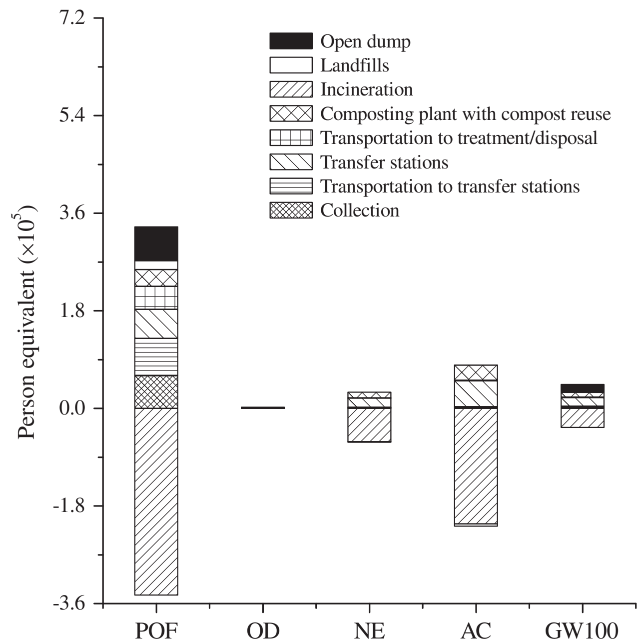


**Fig. 4.** Normalized potential impacts of scenario C. POF: photochemical ozone formation; OD: ozone depletion; NE: nutrient enrichment; AC: acidification; GW100: global warming (100 years).

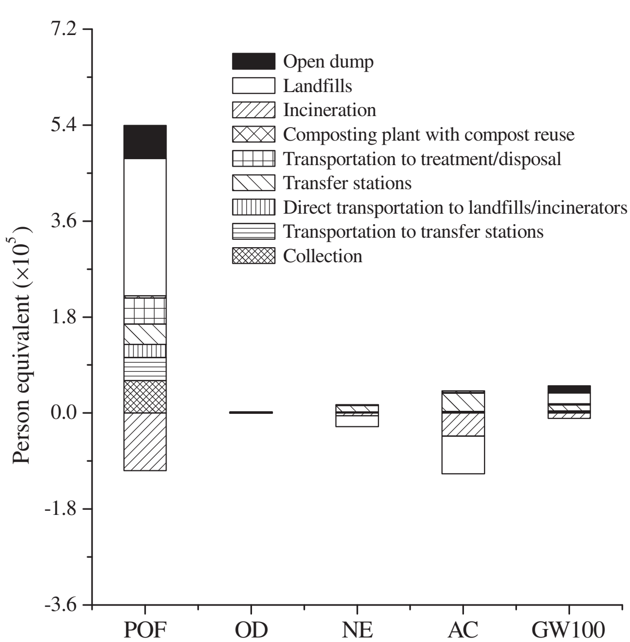


**Fig. 3.** Normalized potential impacts of scenario B. POF: photochemical ozone formation; OD: ozone depletion; NE: nutrient enrichment; AC: acidification; GW100: global warming (100 years).

waste. Therefore, it can be concluded that incineration of mixed waste with high moisture ratio can hardly benefit to the environment in Beijing City, while the source separation to reduce moisture (food waste separation at least) can be an important precondition for beneficial incineration.

### 3.4. Comparison of scenarios A, B and C

The sums of normalized environmental impacts under scenarios A, B, and C are presented in Table 5. The investigated future MSW management systems have significantly different impacts on the environment as compared with the current system. With respect to global warming, the future scenarios (B and C) are significantly better than the current scenario (A), in spite of the significant impact saving on global warming ascribed to biogenic carbon sequestered in the landfills dominating in scenario A. If the sequestered carbon was not linked to the saving on global warming, the loads would have been significantly higher (137,916 PE, 87,316 PE, and 14,438 PE for scenarios A, B, and C, respectively). For nutrient enrichment and acidification, scenario C offers the obvious advantages due to more electricity and heat recovery, together with the compost utilization as substitution of fertilizer. Scenario B shows the worse results in terms of nutrient enrichment and acidification as incineration of mixed waste leads to more $NO_x$ emission. Furthermore, scenario A performs worst in terms of photochemical ozone formation, and waste incineration can improve this by energy recovery and transportation savings resulting from quantitative reduction.

Besides the environmental impacts, cost effectiveness is also a crucial concern for waste system optimization. Introduction of incineration in scenario B will probably increase the cost on waste treatment than scenario A, especially considering the ineffective incineration of waste with high water content. Though extensive use of source separation and incineration in Scenario C will surely increase the cost on waste collection and treatment, it can benefit from the energy recovery and compost utilization, which may counteract the cost increasing in part. Further analysis is required for detailed information on the cost effectiveness of different strategies, and the function of cost calculation in EASEWASTE is already under way.

### 3.5. Sensitivity analysis for scenarios C, C1 (a and b) and C2 (a and b)

Fig. 5 shows the normalized potential impacts of scenarios C1a, C and C1b. The corresponding impacts on global warming varied marginally when the sorting efficiency of food waste was adjusted to 30% (C1a) or 70% (C1b) from 50% (C). This is mainly because more $CH_4$ emission contributes to global warming when more food waste is composted, which counteracts most of the savings from energy recovery in incinerators. Meanwhile, impacts to acidification, nutrient enrichment and photochemical ozone formation changed significantly, revealing that incineration can avoid a lot of N- and S-emissions from substituting energy generated from coal combustion. Furthermore, the use of incinerators is more efficient compared with composting plants in terms of controlling pollution.

**Table 5**
Comparison of environmental impacts under scenarios A, B, and C (PE).

| Environmental impacts | Scenario A | Scenario B | Scenario C |
|---|---|---|---|
| Photochemical ozone formation (POF) | 707292 | 431053 | −9613 |
| Stratospheric ozone depletion (OD) | 1999 | 1950 | 1880 |
| Nutrient enrichment (NE) | −17564 | −9480 | −32332 |
| Acidification (AC) | −74538 | −72464 | −137233 |
| Global warming (GW100) | 62660 | 40878 | 8694 |

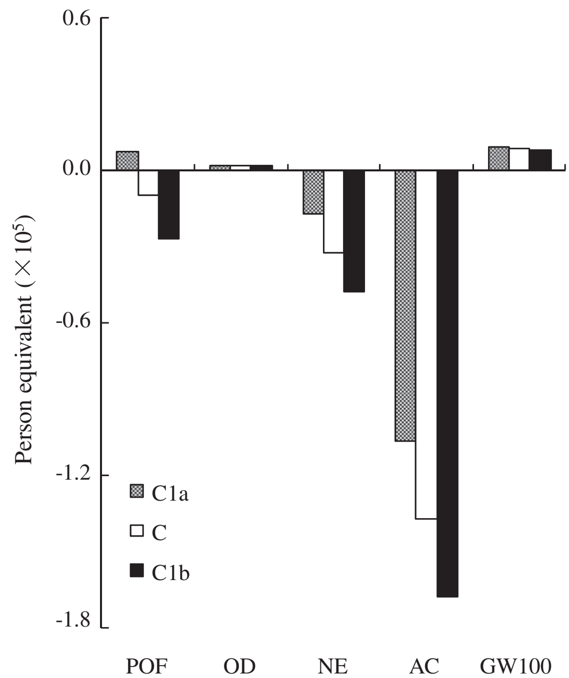


**Fig. 5.** Normalized potential impacts of sensitivity analysis regarding sorting efficiency of food waste: Scenarios C1a (30%), C (50%), and C1b (70%). POF: photochemical ozone formation; OD: ozone depletion; NE: nutrient enrichment; AC: acidification; GW100: global warming (100 years).

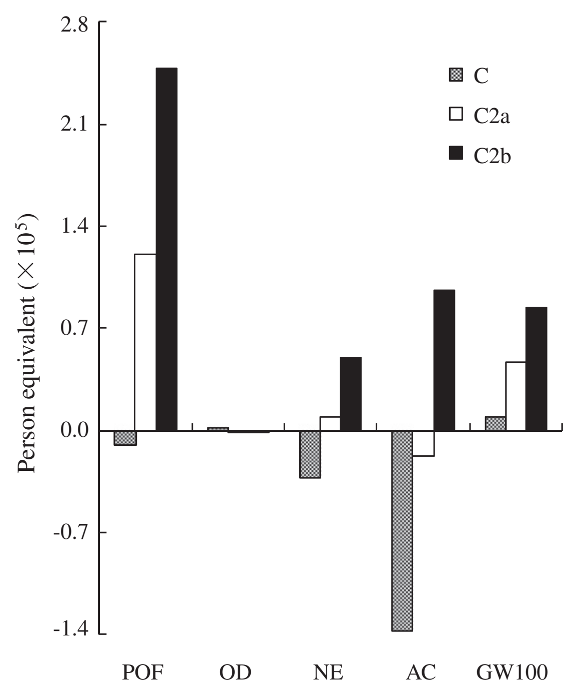


**Fig. 6.** Normalized potential impacts of sensitivity analysis regarding recovery of electricity from incineration: Scenarios C (23%), C2a (17%), and C2b (11%). POF: photochemical ozone formation; OD: ozone depletion; NE: nutrient enrichment; AC: acidification; GW100: global warming (100 years).

When the recovery efficiency of electricity in incineration was decreased to 17% (C2a) or 11% (C2b) from 23% (C), the impacts on global warming, acidification, nutrient enrichment and photochemical ozone formation changed significantly. The impact savings in scenario C can be fully negated, and can even return as loads to the environment, as shown in Fig. 6. This is because that, when coal-based electricity was substituted by the electricity recovered from incineration of the waste, the emissions per kWh electricity produced from coal burning were higher compared with electricity recovered from incineration. Therefore, energy recovery from waste contributes much to emissions reduction, including C, N, S, etc. This reveals that the electricity recovery efficiency in incineration is very crucial to the environmental impacts. In addition, incinerators with very low levels of energy recovery may not compensate for the adverse impacts of pollutant emissions from other treatment processes.

Results from the sensitivity analysis indicate that high energy recovery in waste management is an important issue in obtaining environmental savings on global warming, acidification and nutrient enrichment. This can be improved through different ways, such as increasing the lower heating value of waste by separating food waste with high water content, and enhancing electricity recovery efficiency by improving incineration techniques.

## 4. Conclusions

Based on the current and potential future MSW systems in Beijing City, the environmental impacts on global warming, nutrient enrichment, photochemical ozone formation, acidification, and stratospheric ozone depletion were investigated in this paper. The current MSW system in Beijing City is burdened by waste amounting to over 4 million ton per year. The main treatment and disposal technology used is landfill. This situation results in long-distance transportation of waste, short service lives of facilities, and difficulty of finding new places for landfills. It also leads to significant impacts on photochemical ozone formation and global warming due to the huge amount of methane released from landfills. The alternative strategy of replacing parts of the landfills by incinerators for mixed waste would not result in significant environmental improvements, given the very low heating value of mixed waste, and minimal energy recovery due to high water content of food waste. The long-term planning scenario (i.e., integrated treatment with source separation of food waste) seems a better choice for MSW management in Beijing City due to its benefits in terms of minimizing and avoiding the impacts on photochemical ozone formation, acidification, nutrient enrichment, and global warming, which are mainly because of the strict air emission control in the incinerators, the substitution of coal combustion with recovered power and heat, and the avoided fertilizer production due to compost utilization. These indicate that separation at the source of food waste, which is crucial to decrease the water content and increase the heating value of remaining waste, is an important precondition for the beneficial incineration. Results from sensitivity analysis reveal that the level of energy recovery and the efficiency of food waste sorting at the source are important concerns in obtaining an environmentally friendly waste management system. These results can provide scientific support in the decision-making of the MSW management system in Beijing City.

## Acknowledgement

This work was supported by the open fund of Key Laboratory for Solid Waste Management and Environment Safety, Ministry of Education of China (SWMES 2009-08), National High Technology Research and Development Program of China (No. 2007AA06Z350), and the State Key Project for National Science and Technology (No. 2007BAC16B03). The authors would like to express their sincere gratitude to Dr. Dongbei Yue for his great help on data collection.

## References

Arena, U., Mastellone, M.L., Perugini, F., 2003. The environmental performance of alternative solid waste management options: a life cycle assessment study. Chem. Eng. J. 96, 207–222.

Astrup, T., Mosbak, H., Christensen, T.H., 2006. Assessment of long-term leaching from waste incineration air-pollution-control residues. Waste Manag. 26, 803–814.

Birgisdóttir, H., Bhander, G., Hauschild, M.Z., Christensen, T.H., 2007. Life cycle assessment of disposal of residues from municipal solid waste incineration: recycling of bottom ash in road construction or landfilling in Denmark evaluated in the ROAD-RES model. Waste Manag. 27, S75–S84.

Chen, D., Christensen, T.H., 2010. Life-cycle assessment (EASEWASTE) of two municipal solid waste incineration technologies in China. Waste Manage. Res. 28, 508–519.

Christensen, T.H., Bhander, G., Lindvall, H., Larsen, A.W., Fruergaard, T., Damgaard, A., Manfredi, S., Boldrin, A., Riber, C., Hauschild, M., 2007. Experience with the use of LCA-modelling (EASEWASTE) in waste management. Waste Manage. Res. 25, 257–262.

Hansen, T.L., Bhander, G.S., Christensen, T.H., Bruun, S., Jensen, L.S., 2006a. Life cycle modelling of environmental impacts of application of processed organic municipal solid waste on agricultural land (EASEWASTE). Waste Manage. Res. 24, 153–166.

Hansen, T.L., Christensen, T.H., Schmidt, S., 2006b. Environmental modelling of use of treated organic waste on agricultural land: a comparison of existing models for life cycle assessment of waste systems. Waste Manage. Res. 24, 141–152.

Huang, J., Li, G., Wang, H., Ma, S., Chen, L., 2007. Assessment and investigation methodology for solid waste recycling systems. Environ. Pollut. Control 29, 74–78.

Kaplan, P.O., Ranjithan, S.R., Barlaz, M.A., 2009. Use of life-cycle analysis to support solid waste management planning for Delaware. Environ. Sci. Technol. 43, 1264–1270.

Kirkeby, J.T., Birgisdottir, H., Hansen, T.L., Christensen, T.H., Bhander, G.S., Hauschild, M., 2006a. Environmental assessment of solid waste systems and technologies: EASEWASTE. Waste Manage. Res. 24, 3–15.

Kirkeby, J.T., Birgisdottir, H., Hansen, T.L., Christensen, T.H., Bhander, G.S., Hauschild, M., 2006b. Evaluation of environmental impacts from municipal solid waste management in the municipality of Aarhus, Denmark (EASEWASTE). Waste Manage. Res. 24, 16–26.

Larsen, A.W., Vrgoc, M., Christensen, T.H., Lieberknecht, P., 2009. Diesel consumption in waste collection and transport and its environmental significance. Waste Manage. Res. 27, 652–659.

Li, J., Wang, W., Wang, H., 2007. Planning and management of urban household refuse. China Environmental Sciences Press, Beijing, China.

Manfredi, S., Christensen, T.H., 2009. Environmental assessment of solid waste landfilling technologies by means of LCA-modeling. Waste Manag. 29, 32–43.

Riber, C., Bhander, G.S., Christensen, T.H., 2008. Environmental assessment of waste incineration in a life-cycle-perspective (EASEWASTE). Waste Manage. Res. 26, 96–103.

Rigamonti, L., Grosso, M., Giugliano, M., 2009. Life cycle assessment for optimising the level of separated collection in integrated MSW management systems. Waste Manag. 29, 934–944.

Wang, H., Nie, Y., 2001. Remedial strategies for municipal solid waste management in China. J. Air Waste Manag. Assoc. 51, 264–272.

Wenzel, H., Hauschild, M., Alting, L., 1997. Environmental assessment of products, Vol. 1: methodology tools and case studies in product development. Institute of Product Development, Kluwer Academic Publishers, Hingham, MA, USA.

Zhao, W., der Voet, E.V., Zhang, Y., Huppes, G., 2009a. Life cycle assessment of municipal solid waste management with regard to greenhouse gas emissions: case study of Tianjin, China. Sci. Total Environ. 407, 1517–1526.

Zhao, Y., Damgaard, A., Wang, H., Lu, W., Christensen, T.H., 2009b. Life-cycle assessment of the municipal solid waste management system in Hangzhou, China (EASEWASTE). Waste Manage. Res. 27, 399–406.

Zhao, Y., Si, J., Tian, B., Wang, H., Lu, W., 2007. Method of technology choosing of municipal solid waste treatment and disposal (I): model study. Acta Sci. Nat. Univ. Pekinensis. 43, 834–838 (in Chinese).