JOURNAL OF ENVIRONMENTAL SCIENCES 74 (2018) 1–10

Available online at www.sciencedirect.com

ScienceDirect

www.elsevier.com/locate/jes

JES JOURNAL OF ENVIRONMENTAL SCIENCES

www.jesc.ac.cn

A comparison of chemical MSW compositional data between China and Denmark

Na Yang[1,3], Anders Damgaard[2], Charlotte Scheutz[2], Li-Ming Shao[4], Pin-Jing He[3,4,*]

1. *Shenzhen Academy of Environmental Sciences, Shenzhen 518001, China*
2. *Department of Environmental Engineering, Technical University of Denmark, 2800, Kongens Lyngby, Denmark*
3. *State Key Laboratory of Pollution Control and Resource Reuse, Tongji University, Shanghai 200092, China*
4. *Institute of Waste Treatment and Reclamation, Tongji University, Shanghai 200092, China*

ARTICLE INFO

Article history:
Received 27 July 2017
Revised 17 February 2018
Accepted 18 February 2018
Available online 1 March 2018

Keywords:
Municipal solid waste
Chemical composition
Moisture content
Water diffusion
Consumption and dietary habits
Estimation method

ABSTRACT

Chemical waste compositions are important for municipal solid waste management, as they determine the pollution potentials from different waste strategies. A representative dataset for chemical characteristics of individual waste fractions is frequently required to assess chemical waste composition, but it is usually reported in developed countries and not in developing countries. In this study, a dataset for Chinese waste was established through careful data screening and assessment, named as CN dataset. Meanwhile, a dataset for Danish waste (DK dataset) was also summarized based on previous studies. In order to quantitatively evaluate the reliabilities of CN and DK datasets, the chemical waste compositions in four Chinese cities were estimated by utilizing both of them, respectively. It is indicated that the usage of CN datasets led to significantly lower discrepancies from the actual values based on laboratory analysis in most cases. Within the datasets, the moisture contents of food waste, paper, textiles, and plastics, the carbon content of food waste, as well as the oxygen content of plastics would induce significant divergences, which should be paid special attention when gathering the information. In addition, the fractional waste compositions in China showed similar features with other developing countries but differ significantly with developed countries. Thus the above-mentioned conclusions could also be true in other developing countries.

Introduction

Due to the rapid growth in the amounts of municipal solid waste (MSW) in developing countries, many large cities are faced with a "garbage siege," whereby waste dumping sites originally located far outside the conurbations are now surrounding these rapidly expanding cities, resulting in significant human and environmental impacts (Hu et al., 2012; Wu and Xu, 2013). To design a proper waste management system with reduced environmental impacts, knowledge of waste properties is important (Cleary, 2009). Waste properties are often described in terms of fractional waste compositions and chemical waste compositions. Fractional compositions determine the potential for recycling and energy recovery (Tai et al., 2011), while chemical compositions are essential for estimating pollutant potentials from different waste strategies (Manfredi et al., 2011; Yang et al., 2012, 2013). For example, higher plastic content will increase the heating values of MSW and subsequently make it

* *Corresponding author. E-mail:* solidwaste@tongji.edu.cn (Pin-Jing He).

https://doi.org/10.1016/j.jes.2018.02.010

more effective to recover energy by incineration. However, the fossil carbon contained in plastic fractions would induce higher greenhouse gas (GHG) emissions when MSW is incinerated (Yang et al., 2012).

It is general knowledge that fractional waste compositions differ from one place to another and change over time, due to economic development, waste management policies, and energy supplies (Wang and Nie, 2001; Wei et al., 1997). Correspondingly, chemical waste compositions also change owing to the varied contributions of waste fractions. The chemical compositions of mixed waste can be measured by laboratory analysis (He et al., 2010; Huang et al., 2003; Zhang et al., 2009) or be calculated by combining fractional waste compositions in specific scenarios and the general chemical characteristics of individual fractions (Yang et al., 2012; Zhao et al., 2009a, 2009b, 2011). Fractional waste compositions can be obtained by on-site sorting and weighing, which is frequently conducted due to low technical requirements (Ministry of Housing and Urban–Rural Development of the People's Republic of China, 2009). Laboratory analyzes of the chemical compositions of mixed waste are rarely reported in developing countries, as the sample preparation and analysis is labor-intensive and requires technical knowhow and analytical facilities. The same situation occurs for the chemical characteristics of individual fractions, which conversely often refer to existing datasets. Generally, the chemical characteristics of individual fractions consist of major parameters, *e.g.*, moisture content, organic element content, heating values, and trace parameters, the latter of which usually refer to heavy metal content (Zhang et al., 2008). Heavy metals are usually contained in just a few specific items, for example over 90% of cadmium and mercury in MSW comes from batteries (Riber et al., 2009). The availability or non-availability of these materials in the waste can significantly induce the differences in heavy metal content. It is thus hard to estimate heavy metal content by employing the aforementioned methods. In existing studies, major parameters are often taken into account, whereas trace parameters are often left out. For this study, the major parameters are termed as "chemical characteristics" due to their data availability.

Presently, datasets for the chemical characteristics of individual fractions are extremely scarce. A series of chemical characteristics often referred to was from the handbook written by Tchobanoglous et al. (1993), modified from data obtained in 1966 based on waste in the USA (Kaiser, 1966). In 2007, a comprehensive study focusing on the chemical characteristics of household waste was performed in Denmark (Lagerkvist et al., 2011; Riber et al., 2009), the results of which are available through the EASETECH software package (Clavreul et al., 2014), a widely used tool for life cycle assessment of waste management. In the case of developing countries, there are no comprehensive studies published in this research field. Taking China as an example, researchers (Zhao et al., 2009a, 2009b, 2011) tend to refer to chemical characteristics reported in Western countries (Tchobanoglous et al., 1993). However, this may lead to mis-estimation of chemical compositions. For example, the moisture content of mixed MSW in Hangzhou, estimated by refering to Tchobanoglous et al. (1993), *i.e.*, 43.2% (Zhao et al., 2009b), was remarkably lower than the actual measured values, *i.e.*, 57.5% (Ni and Hong, 2005) and 56.5% (Zhuang et al., 2008), which could evoke subsequent incorrect findings in relation to heating values and the leachate generation potential of waste.

The primary aim of this study was to compile waste property data reported for Chinese cities, including fractional waste compositions, chemical waste compositions, and chemical characteristics of individual waste fractions. Fractional waste compositions in developing countries were additionally compared with those in developed countries and the causes of these differences were identified. The Chinese dataset was finally compared with a Danish dataset, by applying the data to four Chinese cities and contrasting the differences in results between the two datasets.

1. Data source and approaches

1.1. Fractional waste compositions

Fractional waste compositions for 18 Chinese cities were compiled (see details in Table 1). Datasets for megacities as well as smaller cities, and with a certain geographical distribution, are included. Datasets published in the last decade were preferred to older data. Since fractional waste compositions are potentially used for designing waste treatment systems, data were obtained for the remaining mixed waste after source-segregating recyclables in residential areas or waste treatment plants, rather than the originally generated waste in house. Most of the results were average values based on long-term monitoring, while only a few were based on one-time sampling. To be consistent across individual studies and to allow for comparison, the waste was defined to consist of the following eight fractions: Food waste, paper, wood, textiles, plastics, non-combustibles, glass, and metal.

Fractional waste compositions for China were compared to fractional waste composition data for 12 other developing countries and nine developed countries, which were also compiled from published papers (Appendix A Table S1). The eight waste fractions were classified into three main groups according to the degradation velocity, which allowed for a comparison of fractional composition via a ternary diagram between Chinese cities and compositions in other countries. The three degradation groups were: Fast Degradable (FD), represented by food waste, Slowly Degradable (SD), consisting of paper, wood, and textiles, and Non-Degradable (ND), consisting of plastics, non-combustibles, glass, and metal. The degradation velocity was used as the classification criterion, because it determined the performance of waste fractions during treatment processes.

1.2. Datasets for the chemical characteristics of individual waste fractions

Individual waste fractions were chemically characterized in terms of moisture content, heating values, and organic element content. Fractional moisture content was compiled from 11 Chinese cities (Appendix A Table S2). Fractional heating values and organic element content were obtained

Table 1 – Fractional waste compositions and moisture content of municipal solid waste collected in 18 Chinese cities.

City	Waste fraction distributions (% of ww[a])								Moisture content (% of ww)	Sampling description			Reference
	Food waste (FD[b])	Paper (SD[b])	Wood (SD)	Textiles (SD)	Plastics (ND[b])	Non-combustibles (ND)	Glass (ND)	Metal (ND)		Sample origin	Frequency (n[c])	Time	
Beijing	66.2	10.9	3.3	1.2	13.1	3.9	1.0	0.4	63.3	N.A.[d]	N.A.	2008	Wang and Wang (2013)
Chengdu	65.7	13.0	0.9	2.5	12.0	2.1	0.8	2.9	57.3	Waste collection vehicles in a landfill site	One sampling campaign	2002	Huang and Liu (2012)
Chongqing	59.2	10.1	4.2	6.1	16.0	–	3.4	1.1	64.1	1 residential area and two landfill sites	One sampling campaign	2002	Huang et al. (2003)
Dalian	63.7	8.8	0	2.0	18.6	1.2	5.0	0.8	59.7	29 garbage bins in residential area	Twice per month for 1 year (12 sampling campaigns)	2004–05	Zhao (2006)
Guangzhou	53.4	8.3	1.7	10.0	18.6	6.2	1.4	0.4	55.6	N.A.	N.A.	2004–09	Chen (2011)
Hangzhou	64.5	6.7	0.1	1.2	10.1	15.1	2.0	0.3	56.5	40 garbage bins in residential area	One sampling campaigns	2006	Zhuang et al. (2008)
Harbin	44.8	13.4	0.0	4.7	3.3	24.5	6.6	2.7	54.8	Garbage bins in residential area	One sampling campaign	2007	Xie (2009)
Hefei	61.5	1.9	0.9	2.1	11.4	21.7	0.6	–	52.5	5 transfer stations in residential area	N.A.	2005	Jin (2006)
Lanzhou	36.5	9.7	1.4	2.1	11.3	37.8	0.9	0.2	44.3	Unloading places in 5 landfill sites	One time in winter and one time in summer (2 sampling campaigns)	2006	Ji (2007)
Lhasa	57.0	6.0	14.0	7.0	12.0	3.0	0.0	1.0	46.7	Unloading place in a landfill site	Twice per season for 1 year (8 sampling campaigns)	2006	Jiang et al. (2009)
Qingdao	69.0	9.5	2.3	3.0	8.4	6.8	2.2	0.9	56.0	30 garbage bins in residential area	Once per month for 1 year (12 sampling campaigns)	2009	Jiang et al. (2011)
Shanghai	63.8	11.1	1.1	2.6	17.2	1.1	2.7	0.4	58.7	36 garbage bins in residential area	Twice per month for 1 year (24 sampling campaigns)	2008–09	Zhang et al. (2009)
Shenyang	60.4	7.9	2.5	3.6	12.9	5.3	5.4	2.1	61.8	Unloading place in a landfill site	Twice per month for 1 year (24 sampling campaigns)	2008	Ma (2010)
Shenzhen	51.1	17.2	3.9	2.7	21.8	0.8	2.1	0.4	59.7	2 landfill sites and 3 incineration plants	One sampling campaign	2011	SZESMD[e] (2011)
Suzhou	62.6	10.9	0.9	4.2	18.6	0.7	2.0	0.2	60.7	1 transfer station in residential area	Twice every 2 month for 1 year (12 sampling campaigns)	2007	He et al. (2008)
Tianjin	56.9	15.3	1.6	3.9	16.9	2.9	1.6	0.7	55.0	5 transfer stations in residential area	6 times in April (6 sampling campaigns)	2009	He et al. (2010)
Urumqi	76.0	2.4	2.5	4.2	5.4	6.4	2.4	0.8	47.0	1 treatment plant	8 times per month for 1 year (96 sampling campaigns)	2007–08	Shao et al. (2009)
Wuhan	55.3	1.5	8.3	0.0	4.5	27.3	2.0	1.1	53.5.	N.A.	N.A.	2008	Li (2010)

[a] ww, wet waste.
[b] FD, SD, and ND represent the fast, slowly, and non- degradable fraction groups, respectively.
[c] n, number of sampling campaigns.
[d] N.A. not available.
[e] SZESMD, Shenzhen Environmental Sanitary Management Department.

from five literature sources (Appendix A Tables S3–S4). As these data were collected from a large number of researches, the sampling and analysis process were not unified and lead to large variation of the results. To limit the effect of extreme data, the median values, instead of average values, were used to represent the statistical results of the chemical characteristics of individual waste fractions, which were summaries together with standard errors in Table 2 used as the dataset for calculating chemical waste compositions in developing countries (named "**CN** datasets").

For comparison, a dataset of chemical characteristics of individual waste fractions in developed countries was compiled. As a widely used tool for life cycle assessment of waste management, the EASETECH software (Clavreul et al., 2014) contained a comprehensive dataset regarding household waste in Denmark. The Danish waste was divided into more fractions (48 fractions) in comparison to the Chinese case (eight fractions). The 48 waste fractions in the Danish datasets (named "sub-fractions") were merged into eight waste fractions corresponding to those in the Chinese study, to allow for comparison. The chemical characteristics of eight waste fractions (named "**DK** datasets," as shown in Table 2) were calculated according to Eqs. (1) and (2) by combining the chemical characteristics of the sub-fractions (Appendix A **Table S5**) and the distributions of sub-fractions in each of the eight waste fractions (Appendix A **Table S6**).

$$\mathrm{WF}_{\mathrm{mc},j} = \sum_i \left(\mathrm{WSF}_{\mathrm{mc},i} \times \mathrm{W}_{i,j}\right) \tag{1}$$

where $\mathrm{WF}_{\mathrm{mc},j}$ is the moisture content of waste fraction j on a wet weight basis, % of wf (wet waste fraction); $\mathrm{WSF}_{\mathrm{mc}.i}$ is the moisture content of the sub-fractions i on a wet weight basis, % of wsf (wet sub-fraction); and $\mathrm{W}_{i,j}$ is the distribution of sub-fraction i in waste fraction j on a wet weight basis, % of wf.

$$\mathrm{WSF}_{k,j,\mathrm{dry}} = \frac{\sum_i \left[\mathrm{WSF}_{k,i,\mathrm{dry}} \times \left(1\text{–}\mathrm{WSF}_{\mathrm{mc}.i}\right) \times \mathrm{W}_{i,j}\right]}{\sum_i \left[\left(1\text{–}\mathrm{WSF}_{\mathrm{mc},i}\right) \times \mathrm{W}_{i,j}\right]} \tag{2}$$

where $\mathrm{WF}_{k,j,\mathrm{dry}}$ is chemical characteristics k (*i.e.*, heating values and organic element content) of waste fraction j on a dry weight basis, % of df (dry waste fraction); and $\mathrm{WSF}_{k,i,\mathrm{dry}}$ is chemical characteristics k of sub-fraction i on a dry weight basis, % of dsf (dry sub-fraction).

1.3. Estimation of chemical waste compositions

The chemical compositions of mixed waste were calculated using the chemical characteristics of individual waste fractions and fractional waste compositions according to equations Eqs. (3) and (4).

$$\mathrm{MW}_{\mathrm{mc}} = \sum_j \left(\mathrm{WF}_{\mathrm{mc},j} \times \mathrm{W}_j\right) \tag{3}$$

where $\mathrm{MW}_{\mathrm{mc}}$ is the moisture content of mixed waste on a wet weight basis, % of ww (wet waste); and W_j, represents the distribution of waste fraction j of mixed waste on a wet weight basis, % of ww (Table 1).

$$\mathrm{MW}_{k,\mathrm{dry}} = \frac{\sum_j \left[\mathrm{WF}_{k,j,\mathrm{dry}} \times \left(1\text{–}\mathrm{WF}_{\mathrm{mc}.j}\right) \times \mathrm{W}_j\right]}{\sum_j \left[\left(1\text{–}\mathrm{WF}_{\mathrm{mc},j}\right) \times \mathrm{W}_j\right]} \tag{4}$$

Table 2 – CN and DK datasets for chemical characteristics of individual waste fractions (based on Appendix A Tables S2-S4 for CN datasets, and Tables S5 and S6 for DK datasets).

Waste fraction	Moisture content (% of wf[a])	HHV (MJ/kg of df [b])	Organic element content (% of df)					
			C	H	O	N	S	Cl
CN datasets								
Food waste	68.0 ± 5.8[c]	16.3 ± 1.7	36.8 ± 2.3	5.5 ± 0.5	38.6 ± 2.9	2.6 ± 0.5	0.3 ± 0.1	0.82
Paper	43.2 ± 14.1	16.6 ± 1.5	41.3 ± 3.2	5.9 ± 0.4	44.7 ± 3.0	0.3 ± 0.4	0.2 ± 0.1	0.46
Wood	48.0 ± 14.3	18.3 ± 1.1	42.9 ± 4.7	6.1 ± 0.1	42.0 ± 1.0	1.6 ± 1.1	0.1 ± 0.03	0.36
Textiles	43.5 ± 18.6	16.5 ± 2.4	46.3 ± 2.5	6.6 ± 0.3	40.8 ± 2.5	4.4 ± 3.2	0.5 ± 0.5	0.46
Plastics	43.5 ± 15.2	32.6 ± 2.4	60.4 ± 4.0	7.9 ± 0.5	22.3 ± 6.2	0.5 ± 0.7	0.1 ± 0.05	1.9
Non-combustibles[d]	29.6 ± 17.8	–	–	–	–	–	–	–
Glass	2.4 ± 5.7	–	–	–	–	–	–	–
Metal	5.4 ± 2.6	–	–	–	–	–	–	–
DK datasets								
Food waste	72.2	19.8	49.9	6.9	34.4	3.1	0.23	0.82
Paper	24.9	17.6	45.5	6.3	36.2	0.44	0.08	0.13
Wood	47.6	14.4	43.9	5.5	25.4	1.8	0.22	0.24
Textiles	14.2	20.9	53.1	6.4	31.4	2.6	0.38	0.58
Plastics	9.9	30.5	67.0	9.4	9.0	0.90	0.12	3.0
Non-combustibles	14.8	0.91	4.0	0.58	3.0	0.25	0.11	0.43
Glass	7.2	0	0	0	0	0	0.04	0
Metal	11.0	11.7	24.5	3.8	3.6	0.18	0.02	0.04

[a] wf, wet waste fraction.
[b] df, dry waste fraction.
[c] median ± standard errors.
[d] Non-combustibles represents ashes, slags, ceramics, and other non-combustible fines.

where $MW_{k,dry}$ is chemical characteristics *k* (*i.e.*, heating values and organic element content) of mixed waste on a dry weight basis, % of dw (dry waste).

1.4. Comparison of the estimated chemical compositions using CN and DK datasets

To identify which datasets for the chemical characteristics of individual fractions (**CN** datasets and **DK** datasets) were more reliable for estimating the chemical compositions of Chinese waste, actual values were used as the baseline and the difference in percentage terms between actual and estimated values were calculated according to Eq. (5) (for moisture content), Eq. (6) (for LHV, lower heating value), and Eq. (7) (for HHV, higher heating value, and organic element content), respectively. The actual values referred to the laboratory-analyzed chemical compositions of mixed waste according to the existing literature, which were available for Beijing (Wang and Wang, 2013), Chongqing (Huang et al., 2003), Shanghai (Zhang et al., 2009), and Tianjin (He et al., 2010).The estimated values of these four Chinese cities were calculated based on **CN** and **DK** datasets. The actual values and estimated values were both presented in Table 3.

$$DV_{mc} = \frac{MW_{mc}(CN) - MW_{mc}(LA)}{MW_{mc}(LA)} \times 100\% \text{ and } \frac{MW_{mc}(DK) - MW_{mc}(LA)}{MW_{mc}(LA)} \times 100\% \quad (5)$$

where DV_{mc} represents the difference in percentage terms between the estimated and actual values of the moisture content of mixed waste, %; MW_{mc}(CN) and MW_{mc}(DK) represent the estimated moisture content of mixed waste on a wet weight basis, using the CN and DK datasets, respectively, % of ww; and MW_{mc}(LA) represents the laboratory-analyzed moisture content of mixed waste on a wet weight basis, % of ww.

$$DV_{LHV} = \frac{MW_{LHV}(CN) - MW_{LHV}(LA)}{MW_{LHV}(LA)} \times 100\% \text{ and } \frac{MW_{LHV}(DK) - MW_{LHV}(LA)}{MW_{LHV}(LA)} \times 100\% \quad (6)$$

where DV_{LHV} represents the difference in percentage terms between the estimated and actual values of the LHV of mixed waste, %; MW_{LHV}(CN) and MW_{LHV}(DK) represent the estimated LHV of mixed waste on a wet weight basis, using the **CN** and **DK** datasets, respectively, % of ww; and MW_{LHV}(LA) represents the laboratory-analyzed LHV of mixed waste on a wet weight basis, % of ww.

$$DV_{k} = \frac{MW_{k,dry}(CN) - MW_{k,dry}(LA)}{MW_{k,dry}(LA)} \times 100\% \text{ and } \frac{MW_{k,dry}(DK) - MW_{k,dry}(LA)}{MW_{k,dry}(LA)} \times 100\% \quad (7)$$

where DV_k represents the difference in percentage terms between the estimated and actual values for the HHV and organic element content of mixed waste, %; $MW_{k,dry}$(CN) and $MW_{k,dry}$(DK) represent the estimated HHV and organic element content of mixed waste on a dry weight basis, using the **CN** and **DK** datasets, respectively, % of dw; and $MW_{k,dry}$(LA) represents the laboratory-analyzed HHV and organic element content of mixed waste on a dry weight basis, % of dw.

1.5. Identification of the key chemical characteristics of individual waste fractions

To identify the key chemical characteristics of individual fractions impacting on the estimation of chemical composition, the contributions of different chemical characteristics (except for HHV) of individual waste fractions between the **CN** and **DK** datasets and the total wet weight in four Chinese cities (*i.e.*, Beijing, Chongqing, Shanghai, and Tianjin) were calculated according to Eq. (8) (for moisture content) and Eq. (9) (for organic elements). The results are shown in Table 4 as a range of the minimum and maximum value calculated for the four cities and discussed in Section 2.3

$$CTB_{mc,j} = W_j \times \left| \left[WF_{mc,j}(CN) - WF_{mc,j}(DK) \right] \right| \quad (8)$$

Table 3 – Chemical waste compositions in four Chinese cities.

City	Moisture content (of ww [a])	LHV (MJ/kg of ww)	HHV (MJ/kg of dw [b])	Organic element content (% of dw)						Reference
				C	H	O	N	S	Cl	
Laboratory analyzed										
Beijing	63.3	4.6	17.9	39.3	5.4	–	1.0	–	–	Wang and Wang (2013)
Chongqing	64.1	3.7	16.8	35.5	4.4	14.3	1.3	0.24	0.72	Huang et al. (2003)
Shanghai	58.7	5.5	16.9	41.8	6.3	22.5	0.85	0.85	0.90	Zhang et al. (2009)
Tianjin	55.0	6.3	18.1	40.9	5.9	25.3	1.3	0.2	1.0	He et al. (2010)
Estimated using CN dataset										
Beijing	58.7	6.1	18.2	38.4	5.5	32.9	1.6	0.20	0.85	This study
Chongqing	56.4	6.6	18.3	39.8	5.6	32.6	1.7	0.20	0.86	
Shanghai	57.7	6.6	18.8	40.0	5.7	32.4	1.6	0.20	0.92	
Tianjin	56.1	6.8	18.6	39.7	5.6	32.5	1.5	0.19	0.87	
Estimated using DK dataset										
Beijing	54.2	7.9	20.1	48.8	6.8	24.5	1.7	0.17	1.2	This study
Chongqing	50.1	9.3	21.1	50.7	6.9	23.9	1.7	0.18	1.2	
Shanghai	51.8	9.0	21.4	51.0	7.1	23.6	1.7	0.16	1.3	
Tianjin	48.5	9.5	20.8	50.0	6.9	24.0	1.5	0.16	1.2	

LHV: lower heating value; HHV: higher heating value; DK: Danish waste dataset; CN: Chinese waste dataset.
[a] ww, wet waste.
[b] dw, dry waste.

Table 4 – Contributions of the different chemical characteristics of individual waste fractions between CN and DK datasets to the total waste weight (ranges of results in four Chinese cities in Appendix A Table S7) (% of ww[a]).

	Moisture content	Organic element content					
		C	H	O	N	S	Cl
Food waste	2.39–2.78	1.55–2.62	0.17–0.28	0.50–0.84	0.06–0.11	0.008–0.013	0.0002–0.0004
Paper	1.85–2.81	0.14–0.33	0.01–0.03	0.29–0.68	0.005–0.011	0.002–0.005	0.01–0.03
Wood	0.005–0.018	0.01–0.02	0.003–0.014	0.1–0.43	0.001–0.005	0.0008–0.0036	0.0007–0.0030
Textiles	0.35–1.78	0.06–0.15	0.002–0.004	0.09–0.21	0.02–0.04	0.0009–0.0022	0.001–0.003
Plastics	4.41–5.8	0.48–0.65	0.11–0.15	0.96–1.31	0.03–0.04	0.004–0.006	0.08–0.11
Non-combustibles	0.16–0.58	–	–	–	–	–	–
Glass	0.05–0.16	–	–	–	–	–	–
Metal	0.02–0.06	–	–	–	–	–	–

[a] ww, wet waste.

where $CTB_{mc,j}$ is the contribution of the difference between the moisture content of waste fractions j in the **CN** and **DK** datasets and the total waste weight, % of ww; and $WF_{mc,j}(CN)$ and $WF_{mc,j}(DK)$ represent the moisture content of the waste fraction j on a wet weight basis in the **CN** dataset and **DK** dataset (Table 2), respectively.

$$CTB_{k,j} = W_j \times [1 - WF_{mc,j}(LA)] \times |[WF_{k,j,dry}(CN) - WF_{k,j,dry}(DK)]| \quad (9)$$

where $CTB_{k,j}$ is the contribution of the difference between organic element k of waste fraction j in the **CN** and **DK** datasets and the total waste weight, % of ww; $WF_{mc,j}(LA)$ is the laboratory-analyzed moisture content of waste fraction j (Appendix A **Table S2**); and $WF_{k,j,dry}(CN)$ and $WF_{k,j,dry}(DK)$ represent the content for organic element k of waste fraction j on a dry weight basis in the **CN** datasets and **DK** datasets (Table 2), respectively.

2. Results and discussion

2.1. Regional variance of fractional compositions

Fig. 1 compares fractional waste compositions between China and other developing countries as well as with developed countries. The data are clearly clustered in two groups, representing China and developing countries in one cluster and developed countries in another cluster. Non-degradable fractions (including plastics, non-combustibles, glass, and metal) contributed similarly in developed and developing countries but showed a large variation, ranging between 15% and 50%. The main difference, however, was the allocation of slowly degradable fractions (including paper, wood, and textiles) and fast degradable waste fractions (*i.e.*, food waste). The greatest divergence occurred for slowly degradable fractions, where the contribution to total wet weight was more than 30% in developed countries and less than 30% in developing countries. Correspondingly, the ratios of fast degradable fractions also differed a lot, *i.e.*, 20% to 45% in developed countries and 35% to 75% in developing countries. On the basis of previous studies (He et al., 2010; Shenzhen Environmental Sanitary Management Department, 2011), the paper fractions of MSW in Chinese cities mainly consisted of toilet paper or tissue paper. A study about the degradation features of individual waste fractions demonstrated that toilet paper possessed degradability similar to most of the food waste fractions, which were significantly higher than green waste and newspapers (Zheng et al., 2013). Therefore, if toilet papers were accounted for as a fast degradable fraction, the already high contributions of fast degradable fractions in China would be even higher than in developed countries.

Focusing on waste fraction distributions in Chinese cities (Table 1), two common features existed: (1) The fraction of food waste was the largest fraction contributing to the composition of MSW, which often accounted for more than 50% in weight in most cities. This is attributed to the large share that food consumption has of the total household consumption expenditure (*i.e.*, around 30% (National Bureau of Statistics of the People's Republic of China, 2015)), but also to the simple packaging and transportation system for food materials. On the one hand, the simple packaging reduces paper and plastic waste fractions. On the other hand, the less packaging and low degree of organization will induce more food wastage during transportation to the consumer (*e.g.*, the outer parts of vegetables are usually inedible and are discarded as waste). (2) The fractions of recyclables (*i.e.*, wood, textiles, glass, and metal) were significantly lower. For instance, each recyclable fraction contributed less than 5%, and the sum of the four recyclables contributed no more than 10%. This could be explained by effective household recovery performance and the existence of waste scavengers (Zhang et al., 2010). (3) The fraction that showed the most variation between the 18 Chinese cities was non-combustibles, which was less than 3% in Suzhou, Shenzhen, Shanghai, Dalian, Chengdu, and Tianjin, but higher than 20% in Hefei, Harbin, Wuhan, and Lanzhou. The large variation can be attributed mainly to the difference in energy infrastructure. In Hefei, Harbin, Wuhan, and Lanzhou, heating-supplying is necessary in winter, however, the central heating systems were lacked in Wuhan and Hefei, or with limited coverage area in Lanzhou and Harbin. Coal-fired separate heating system existed in those cities due to its low technology and cost requirement, and lack of nature gas network (Gou et al., 2012). Those separate heating system generate large amount of slag and the slag goes into household waste management system.

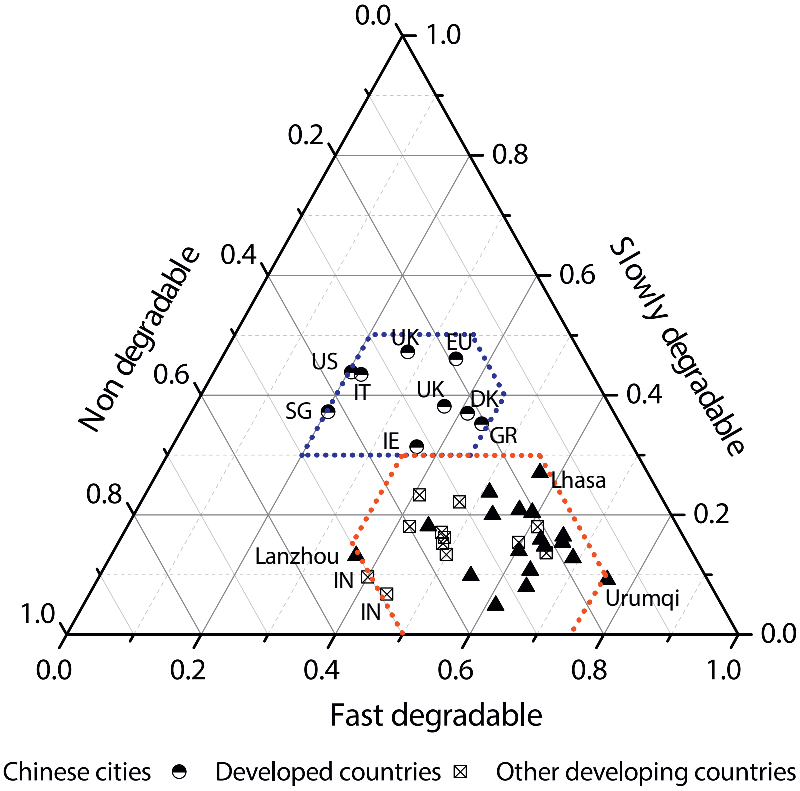

Fig. 1 – Comparison of fractional waste compositions in China and other countries. The blue and red dotted lines represent the ranges of fractional compositions for developed countries and developing countries, respectively. US, EU, UK, IT, DK, GR, IE, SG, and IN are abbreviations for the United States of America, European Union, United Kingdom, Italy, Denmark, Greece, Ireland, Singapore, and India.

2.2. Comparison of estimated chemical waste compositions, using the CN and DK datasets

Fig. 2 presents a comparison of the chemical compositions (moisture content, LHV, HHV, carbon, hydrogen, oxygen, nitrogen, sulfur, and chlorine) of mixed waste. The comparison is shown as the difference in percentage terms between actual values based on the laboratory analysis of mixed waste and estimated values calculated based on CN datasets (gray columns) and DK datasets (white columns). For the frequently used parameters, including moisture content, higher heating values (HHV), carbon content, and hydrogen content, the discrepancies between estimated values using **CN** datasets and the actual values were mostly less than 15%. However, discrepancies using the **DK** datasets were as high as 10% to 40%. Considering nitrogen, sulfur, and chlorine content, the difference between estimated and actual values varied significantly among the cities, and could be as high as 80% in Shanghai. This could be explained by their lower weight in mixed waste (*i.e.*, less than 2% of dry weight), implying the lower the contributions in waste weight, the higher the divergences and uncertainties for estimation. Nevertheless, the higher representativeness of the **CN** datasets was also apparent for those three elements.

The only exception was for oxygen content in Chongqing, Shanghai, and Tianjin, where the difference between estimation results using **CN** datasets and the actual value were one, eight, and five times higher than the estimation results using **DK** datasets. This could be attributed to the lack or low quality of original data for oxygen in the **CN** datasets, which limited representation of oxygen element in the **CN** datasets. Even for the reported values, they were not directly analyzed in the laboratory but were estimated by subtracting other element contents from total VS.

In order to design a proper MSW treatment strategy, LHV is an important parameter, due to its direct link to potential energy recovery. However, discrepancies between the estimated and actual results were extremely high, namely 9%–78% using the **CN** datasets and 50%–150% using the **DK** datasets, because LHV was not an originally tested value but was instead calculated from HHV and moisture content, and thus the discrepancy was a combination of uncertainty between the latter two parameters.

2.3. Key chemical characteristics of individual fractions influencing chemical composition estimation

The contributions of the different chemical characteristics of individual waste fractions between the **CN** and **DK** datasets in relation to the total waste weight in four Chinese cities (*i.e.*, Beijing, Chongqing, Shanghai, and Tianjin) are presented in Table 4 (detailed information shown in Appendix A **Table S7**). Divergences were found to be over 1% of the total waste weight

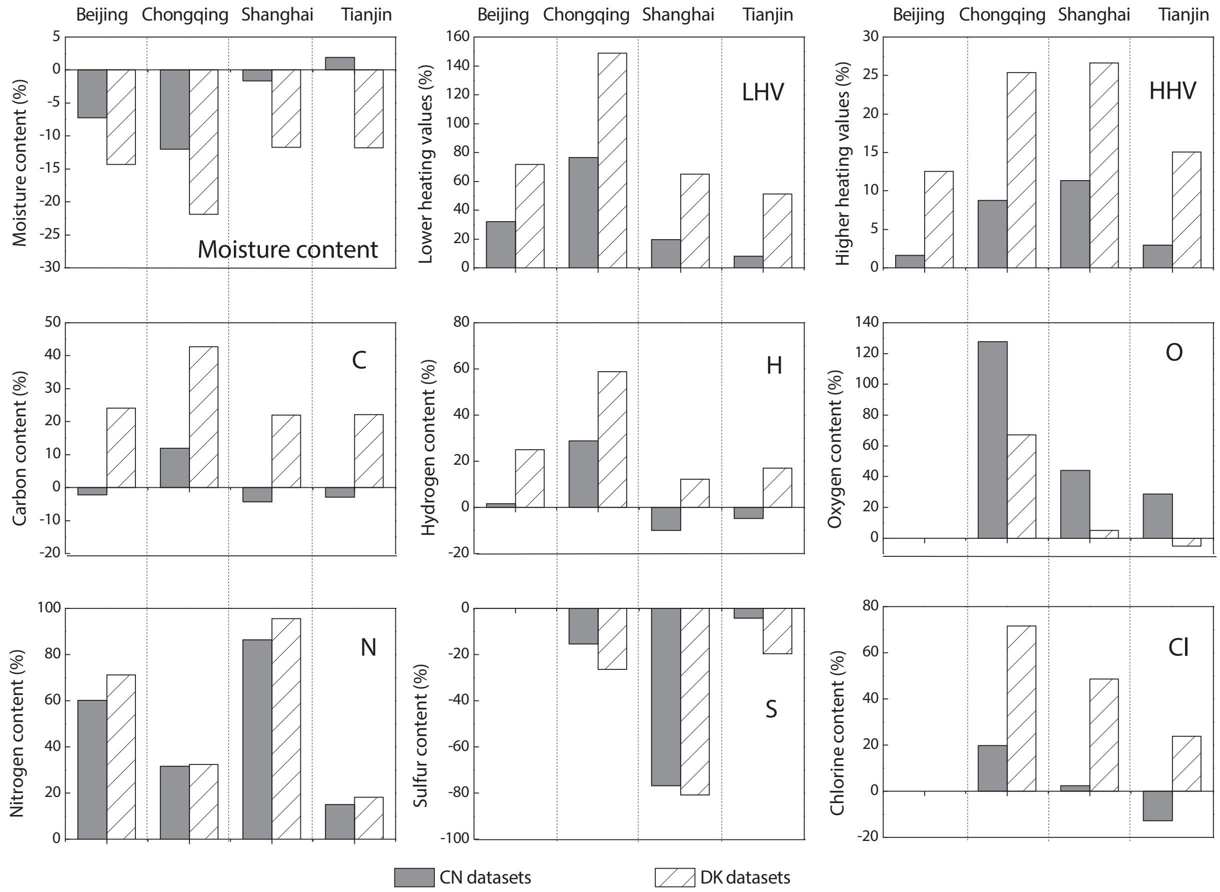

Fig. 2 – Difference in percentage terms between the estimated chemical compositions and laboratory-analyzed values in four Chinese cities. (LHV, lower heating value; HHV, higher heating value).

for the moisture content of food waste, paper, textiles, and plastics, the carbon content of food waste, as well as the oxygen content of plastics. These chemical characteristics of waste fractions were key parameters during the chemical waste composition estimations, and so special attention should be paid during data collection. The reason why the above parameters between the **CN** and **DK** datasets show large differences will be discussed in the following.

2.3.1. Moisture diffusion

In Chinese cities, the moisture content of paper, plastic, wood, textiles, and non-combustible fractions was significantly higher than in Denmark (Table 2). This could be attributed the higher proportions of food waste fractions (>50%) in China. Owing to the extremely high moisture content (often around 80%) of food waste, water contained in food scraps would diffuse into other fractions, *i.e.*, paper, wood, ashes, slag, and textiles, when individual fractions were mixed in waste bins and collection vehicles. In China, because of the effective household recovery performance of office paper and cardboard, the fractions of paper in mixed waste were often toilet paper, sanitary towels, and diapers (Shenzhen Environmental Sanitary Management Department, 2011), which possessed high absorption capacities. In the case of fractions of plastic, shopping bags and disposable dishware were commonly found (Shenzhen Environmental Sanitary Management Department, 2011), on which large amounts of oil and food scraps were often stuck. When researchers analyzed the waste properties, they usually sample mixed waste from waste bins or from treatment plants, sort fractions, and then tested the weight and chemical characteristics of individual fractions. However, the distributions of waste fractions obtained by this approach differed from the waste fractions originally generated in households (Dahlén and Lagerkvist, 2008; Sfeir et al., 1999). For example, the percentages of paper, wood, textiles, plastics, and non-combustibles would be overestimated and food waste fractions underestimated. A scheme illustrating this issue is shown in Appendix A **Fig. S1**.

In Denmark, water diffusion from food waste into other fractions is not as obvious as in China, since there is not so much food waste in mixed waste (around 40% in wet weight). Thus, the moisture content of individual fractions in DK datasets could be considered closer to the original generation (Edjabou et al., 2015). Therefore, when we utilize the fraction waste compositions after mixing (city-specific values seen in Table 1) and the chemical characteristics of individual fractions before mixing (**DK** datasets seen in Table 2) for estimating chemical compositions, a mismatch occurs and results in an underestimation of the moisture content of mixed waste.

2.3.2. Carbon content of food waste

The average carbon content of food waste fractions in Chinese cities was 36.8%, which was significantly lower than the values in Denmark (49.5%) as well as other developed countries (42.1% to 50.8% as shown in Appendix A **Table S8**). This could be explained by the consumption and dietary customs of Chinese citizens: (1) Vegetables and grains, rather than animal food, make up the main food supply in Chinese households. This is consistent with the lower C/O ratios of food waste in China (0.91 and 0.98 based on the data in Appendix A **Table S4**) than in developed countries (around 1.28 to 1.40 as shown in Appendix A **Table S8**), since vegetables are mainly composed of carbohydrate, while meat is made up of protein and lipid. (2) Food supplied in Chinese markets is often not cleaned or packaged, *e.g.*, the outer leaves of cabbage, the roots of celery, and the bones of fish and meat are usually sold together with the products. Thus, people have to clean those parts before or after cooking, which, along with high ash content, will be added to the MSW stream and indirectly decrease the carbon content of food waste fractions in Chinese waste.

2.3.3. Oxygen content of plastics

The oxygen content of plastics in CN datasets was 22.3% of df, which was twice as high as the data in DK datasets (9.0% of df). Simultaneously, the C/O ratio of plastics in CN datasets was 2.7, which was significantly lower than the data in DK datasets (7.4). These features were also found for the oxygen content of paper, wood, textile in different levels. The pure paper, wood, textile and plastics were agriculture and industrial products with similar standard in the world. The element compositions of those goods should not differ a lot between the two countries. Thus, the high oxygen content of those waste fractions could be attributed to the pollution of food waste, which was the essential difference between Chinese waste and Danish waste. This assumption was confirmed by our personal experience during waste sampling: food scraps were often found stuck on shopping bags, disposable dishware, as well as tissue paper in household waste bins, and food waste could also stuck on other waste fractions during waste collection and transportation.

3. Conclusion

The fast degradable fraction consisting of food waste was the dominant waste fraction in Chinese MSW (>50% of ww), as was also the case for other developing countries. This was different from developed countries, where waste was found mainly to consist of slowly degradable (paper, wood, and textiles) and non-degradable fractions (plastics, non-combustibles, glass, and metal). Moisture content in mixed waste in China was usually higher than the values in developed countries. Also, a higher moisture content for individual waste fractions was seen for China, which is due to the diffusion of water from the high content of food waste into other waste fractions like paper, plastics, *etc.* Adhered food waste caused notable high moisture content and oxygen content for plastic fractions in Chinese waste. In addition, the carbon content of food waste in China was significantly lower than in developed countries, due to diverse consumption and dietary habits. All of these divergences of MSW between China and developed countries will result in differences in engineering and chemical behaviors as well as pollution potentials during waste treatment processes. Therefore, it is not always a reliable practice to estimate waste properties in developing countries by using data sources for the chemical characteristics of individual waste fractions obtained from developed countries, which has been done frequently by researchers till now. If one intends to estimate waste properties in developing countries, it is recommended to obtain not only waste fraction compositions, but also the moisture content of each fraction in the specific scenario—at the very least. If it is impossible to test chemical characteristics of individual fractions in the specific scenario, the dataset summarized in this study, based on Chinese waste, could be referred to by practitioners.

Acknowledgment

The work was supported by the National Environmental Protection Standard Project (2015-4), and the Shanghai Technical Standard Projects (Nos. 14DZ0501500, DB31ZB5-15043).

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jes.2018.02.010.

REFERENCES

Chen, X.M., 2011. Methan utilization in municipal solid waste landfill. Environmental Engineering. Jinan University, Guangzhou.

Clavreul, J., Baumeister, H., Christensen, T.H., Damgaard, A., 2014. An environmental assessment system for environmental technologies. Environ. Model. Softw. 60, 18–30.

Cleary, J., 2009. Life cycle assessments of municipal solid waste management systems: a comparative analysis of selected peer-reviewed literature. Environ. Int. 35, 1256–1266.

Dahlén, L., Lagerkvist, A., 2008. Methods for household waste composition studies. Waste Manag. 28, 1100–1112.

Edjabou, M.E., Jensen, M.B., Götze, R., Pivnenko, K., Petersen, C., Scheutz, C., et al., 2015. Municipal solid waste composition: sampling methodology, statistical analyses, and case study evaluation. Waste Manag. 36, 12–23.

Gou, J.F., Zeng, Z.Z., Ji, A.M., Wang, H., Wang, H.C., 2012. Physical composition and moisture characteristics of municipal solid waste of Lanzhou City. Environ. Eng. 20, 101–105.

He, S., Zhu, S.Y., Yu, L.Q., 2008. Characteristics analysis and treatment countermeasures of domestic waste in Suzhou city. Environ. Sanitation Eng. 16, 62–64.

He, J.B., Yao, Q.J., Han, Z.M., An, J.J., Liu, K.Q., Tang, Y., et al., 2010. Investigation and analysis of domestic waste within the south area of Haihe river in Tianjin Binhai new area. Environ. Sanitation Eng. 18, 7–10.

Hu, X.J., Zhang, M., Yu, J.F., Zhang, G.R., 2012. Food waste management in China: status,problems and solutions. Acta Ecol. Sin. 32 (14), 4575–4584.

Huang, M.X., Liu, D., 2012. Characteristics and compositions of municipal solid waste in Sichuan Province. Environ. Monit. China 28, 121–123.

Huang, B.S., Li, X.H., Wang, L.A., Cui, Z.Q., 2003. Analysis of physicochemical property and discussion of disposal of MSW in the urban zone of Chongqing city. J. Chongqing Univ. 26, 9–13.

Ji, A.M., 2007. The Analysis of Physical Characteristics and Incinerating Feasibility of Municipal Solid Waste in Lanzhou (in Chinese). Environmental Engineering. Lanzhou University, Lanzhou, China.

Jiang, J.G., Lou, Z.Y., Ng, S., Luobu, C., Ji, D., 2009. The current municipal solid waste management situation in Tibet. Waste Manag. 29, 1186–1191.

Jiang, Z., Zhang, W.X., Qi, W.J., 2011. Physical properties and change regularity of domestic waste in Qingdao city. Environ. Sanitation Eng. 19, 36–41.

Jin, J., 2006. Research on property of household waste in Hefei and bio-waste treated by earthworm. Environmental Engineering, Hefei University of Technology, Hefei, China.

Kaiser, E.R., 1966. Chemical analysis of refuse compounds. National Incinerator Conference. ASME, New York.

Lagerkvist, A., Ecke, H., Christensen, T.H., 2011. Waste generation and characterization: 2.1 Waste characterization: approaches and methods. In: Christensen, T.H. (Ed.), Solid Waste Technoloty & Management. Blackwell Pulishing Ltd., Chichester, United Kingdom.

Li, L., 2010. Sustainable development research on the urban and rural domestic refuse disposal in Wuhan. Ecol. Econ. 5, 156–158.

Ma, Z.Z., 2010. Domestic wasteinvestigation and disposal method in Shenyang city. Environ. Sanitation Eng. 18, 13–18.

Manfredi, S., Tonini, D., Christensen, T.H., 2011. Environmental assessment of different management options for individual waste fractions by means of life-cycle assessment modelling. Resour. Conserv. Recycl. 55, 995–1004.

Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2009. Sampling and Analysis Methods for Domestic Waste, Beijing.

National Bureau of Statistics of the People's Republic of China, 2015. China Statistical Yearbook, Beijing.

Ni, N., Hong, G.C., 2005. Physiochemical properties and treatment countermeasure of domestic waste in Hangzhou city. Environ. Sanitation Eng. 13, 31–36.

Riber, C., Petersen, C., Christensen, T.H., 2009. Chemical composition of material fractions in Danish household waste. Waste Manag. 29, 1251–1257.

Sfeir, H., Reinhart, D.R., McCauley-Bell, P.R., 1999. An evaluation of municipal solid waste composition bias sources. J. Air Waste Manag. Assoc. 49 (9), 1096–1102.

Shao, H.W., Xu, W.L., Kong, J.J., Patiguli, Ge, C.H., Zhang, Y.S., et al., 2009. Investigation and estimation of domestic waste in Urumqi. Environ. Sanitation Eng. 17, 10–12.

Shenzhen Environmental Sanitary Management Department, 2011. Statistical Analysis of Municipal Solid Waste Characteristics in Shenzhen (Shenzhen, China).

Tai, J., Zhang, W., Che, Y., Feng, D., 2011. Municipal solid waste source-separated collection in China: a comparative analysis. Waste Manag. 31, 1673–1682.

Tchobanoglous, G., Theisen, H., Vigil, S., 1993. Integrated Solid Waste Management: Engineering Principles and Management Issues. McGraw-Hill.

Wang, H.T., Nie, Y.F., 2001. Municipal solid waste characteristics and management in China. J. Air Waste Manage. Assoc. 51, 250–263.

Wang, H., Wang, C.M., 2013. Municipal solid waste management in Beijing: characteristics and challenges. Waste Manag. Res. 31, 67–72.

Wei, J.B., Herbell, J.D., Zhang, S., 1997. Solid waste disposal in China-situation, problems and suggestions. Waste Manag. Res. 15, 573–583.

Wu, Y.C., Xu, L.F., 2013. Analysis of the barrier factors of municipal solid waste classification recycling. In: Zhao, J., Iranpour, R., Li, X., Jin, B. (Eds.), Advances in Materials Research. Trans Tech Publications Ltd., Zurich, Switzerland, pp. 2618–2621.

Xie, B., 2009. Study on the Waste Degradation Behavior and Stabilization of Dumping Sites in Northeasten China. Environmental Science and Engineering Harbin Institute of Technology, Harbin, China.

Yang, N., Zhang, H., Chen, M., Shao, L.M., He, P.J., 2012. Greenhouse gas emissions from MSW incineration in China: Impacts of waste characteristics and energy recovery. Waste Manag. 32, 2552–2560.

Yang, N., Zhang, H., Shao, L.M., Lü, F., He, P.J., 2013. Greenhouse gas emissions during MSW landfilling in China: influence of waste characteristics and LFG treatment measures. J. Environ. Manag. 129, 510–521.

Zhang, H., He, P.J., Shao, L.M., 2008. Flow analysis of heavy metals in MSW incinerators for investigating contamination of hazardous components. Environ. Sci. Technol. 42, 6211–6217.

Zhang, Y., Yang, X.H., Wang, X.Y., 2009. Survey Report of MSW Characteristics in Shanghai. Shanghai Institute for Design & Research on Environmental Engineering, Shanghai, China.

Zhang, D.Q., Tan, S.K., Gersberg, R.M., 2010. Municipal solid waste management in China: status, problems and challenges. J. Environ. Manag. 91, 1623–1633.

Zhao, W.W., 2006. Survey and analysis of municipal domestic waste in centre area of Dalian city. Environ. Sanitation Eng. 14, 29–30.

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

Zhao, Y., Christensen, T.H., Lu, W.J., Wu, H.Y., Wang, H.T., 2011. Environmental impact assessment of solid waste management in Beijing City, China. Waste Manag. 31, 793–799.

Zheng, W., Phoungthong, K., Lu, F., Shao, L.M., He, P.J., 2013. Evaluation of a classification method for biodegradable solid wastes using anaerobic degradation parameters. Waste Manag. 33 (12), 2632–2642.

Zhuang, Y., Wu, S.W., Wang, Y.L., Wu, W.X., Chen, Y.X., 2008. Source separation of household waste, a case study in China. Waste Manag. 28, 2022–2030.