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Evaluation of a classification method for biodegradable solid wastes using anaerobic degradation parameters

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ABSTRACT

We studied the biochemical and anaerobic degradation characteristics of 29 types of materials to evaluate the effects of a physical composition classification method for degradable solid waste on the computation of anaerobic degradation parameters, including the methane yield potential (L_0), anaerobic decay rate (k), and carbon sequestration factor (CSF). Biochemical methane potential tests were conducted to determine the anaerobic degradation parameters of each material. The results indicated that the anaerobic degradation parameters of nut waste were quite different from those of other food waste and nut waste was classified separately. Paper was subdivided into two categories according to its lignin content: degradable paper with lignin content of <0.05 g g VS^{-1}, and refractory paper with lignin content >0.15 g g VS^{-1}. The L_0, k, and CSF parameters of leaves, a type of garden waste, were similar to those of grass. This classification method for degradable solid waste may provide a theoretical basis that facilitates the more accurate calculation of anaerobic degradation parameters.

1. Introduction

Global municipal solid waste (MSW) production reached 1.3 billion tonnes per year in 2010 and it is expected to increase to 2.2 billion tonnes per year by 2025 (Hoornweg and Bhada-Tat, 2012). The disposal of this increasing volume of waste in a controlled and sustainable manner is a significant challenge. Despite the push to divert waste from landfills to alternative recycling and recovery processes, landfill is still the main method for waste disposal in many countries. In 2010, 54% of MSW went to landfill in the United States (US EPA, 2010) while in 2011, 77% of the MSW in China was disposed of in landfills (China NBS, 2012).

The anaerobic decomposition of waste in landfill leads to in the generation of greenhouse gases, including methane and carbon dioxide. Some of the methane generated by landfill can be collected via landfill gas collection systems and oxidized in the landfill cover layer (He et al., 2011), but the methane generated from landfill still makes the fourth largest contribution to anthropogenic methane emissions worldwide (IPCC, 2007a,b; Chen et al., 2008). Landfill is also a carbon sink for recalcitrant organics. Churkina et al. (2009) reported that landfill was the third biggest carbon store in human settlements in the United States. Furthermore, the anaerobic decay rate of waste affects the collection efficiency of landfill gas collection systems and the methane emissions from the landfill cover layer. In general, the gas collection efficiency decreases with increases in the anaerobic decay rate (Barlaz et al., 2009). Therefore, anaerobic degradation parameters such as the methane yield potential (L_0), anaerobic decay rate (k), and carbon sequestration factor (CSF) are used widely to estimate the environmental impact of landfill.

Different waste compositions produce different values of L_0, k, and CSF. Thus, the Intergovernmental Panel on Climate Change (IPCC) model (IPCC, 2006) uses the individual categories of waste to calculate the anaerobic degradation parameters. IPCC divides wastes into food waste, nappies, paper, garden, sludge, wood, textiles, and industry. However, even a simple category may contain diverse components, so this classification method may lead to large differences between the calculated values and the actual results in a real landfill. The MSW in the United States contains a large proportion of lignocellulosic waste, including paper (29%), garden waste (13%), and wood (6%) (US EPA, 2010), so some researchers (Barlaz, 1998; Cruz and Barlaz, 2010; Eleazar et al., 1997; Wang et al., 2011) have suggested further subdividing paper into office paper, coated paper, newspaper, and corrugated card-

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board, subdividing garden waste into grass, leaves, and branches, subdividing wood into lumber, particleboard, oriented strand board, medium-density fiberboard, and plywood. By contrast, the food waste content of the MSW produced by developing countries is more significant. For example, wood and garden waste accounted for only 1.1 ± 0.2% of the MSW in Shanghai, while food waste and paper accounted for 63.8 ± 4.6% and 11.1 ± 1.2%, respectively in 2008–2009. Toilet paper comprised most of the paper waste in Shanghai MSW (Shanghai Environmental Engineering Design and Science Academy, 2009). Thus, the anaerobic degradation parameters of food waste-rich MSW may differ according to their food waste compositions, i.e., food waste with a high lipid content has a relatively high methane yield potential (Cho et al., 2013). Unfortunately, there have been few reports of food waste classification methods, and the classification method for paper is still in need of improvement.

The lysimeter method is used widely to determine anaerobic degradation parameters (US EPA, 2005a). However, lysimeter experiments are very time-consuming so many studies have preferred to obtain the anaerobic degradation parameters using a biochemical methane potential (BMP) assay (Angelidaki et al., 2009; Owens and Chynoweth, 1993; Bogner, 1990).

The main purpose of this study was to investigate the rationality of waste types generalization according to different purposes, e.g., to estimate greenhouse gas emission, to estimate landfill gas production rate, or to estimate carbon sink volume. And the present research also found some special wastes that should be paid attention to when the quantity of the special waste is large. We calculated the anaerobic degradation parameters of each material using BMP tests. And then, cluster analysis was performed using the anaerobic degradation parameters to develop an appropriate classification method for biodegradable solid waste, including food waste, lignocellulosic waste, and fabric.

2. Materials and methods

2.1. Degradation material and inocula

The method which is based on production and consumption quantity of each material is used widely to determine waste statistics (Martin et al., 1995; US EPA, 2005b). In the present study, we selected representative biodegradation materials based on the production and biochemical characteristics of materials, as well as the existing classification method used for biodegradable solid waste. The reasons for choosing these materials were shown in Table 1. In total, 29 types of materials were evaluated.

Each material was prepared as it would have been discarded prior to being contaminated by other refuse components. Grass, leaves, and wood were obtained from gardens and roadsides in Shanghai, China. Paper, fabric, meat, bone, fruit, and vegetables were obtained from local markets before mixed collections.

Size is a very important parameter that affects the rate of methane production but not the ultimate biogas production (Angelidaki et al., 2009). Paper and fabric were shredded using a shredder (S303, Comix, Shenzhen, Guangzhou province, China). Fat pork was grounded with a mincer. Other materials were dried using a vacuum freeze-drier (FD-8, BOYIKANG, China), before shredding with a heavy cutting type grinding apparatus (SM2000, Retsch, Germany) and an ultracentrifugal shredder (ZM200, Retsch, Germany) to obtain a uniform sample size no greater than 1 mm. The bleached newspaper was used to represent the paper of high lignin content.

The inoculum used in the BMP test was the digestate from an anaerobic digestion plant, which treated a mixture of sludge and food waste. The digestate was screened through a 1.2 mm screen and centrifuged at 2000*g* for 10 min at room temperature, before the sediment was used as the inoculum. The inoculum had a total solids (TS) content of 23.8 ± 1.7 wt% and the volatile solids (VS) were 81.9 ± 2.5 wt% of the TS.

2.2. Biochemical methane potential (BMP) assay

Glass bottle reactors with a 1 l volume were used for the BMP assay. Each reactor contained the individual materials, nutrient medium, and inoculum. Raposo et al. (2011) suggested that an inoculum-to-substrate ratio (ISR) of $\geqslant 2$ has never been reported as inhibitory. In the present study, therefore, each bottle contained 100 g (wet weight) of inoculum, 400 g of nutrient medium, and 10 g (dry weight) of the substrate, except for the reactors that contained toilet paper, apple core and peel, orange peel, grapefruit peel, and potato, which used 5 g (dry weight) of substrates because preliminary tests indicated that a higher ISR was required to avoid acidification. The nutrient medium was prepared according to the method described by Angelidaki et al. (2009) and was used to minimize any potential nutrient shortages during biodegradation, as well as to provide a sufficient buffering capacity. A blank reactor that contained inoculum only was also incubated to measure the background methane production.

Before the start of the experiment, each reactor was sealed with butyl rubber and an aluminum cap, followed by sufficient purging with 99.9% of N_2 gas to maintain an anaerobic condition. The bottles were incubated at mesophilic temperatures (35 °C) in a thermostatic room and shaken once each day. Biogas production was determined based on the gas pressure and the carbon dioxide and methane content in the headspaces of the bottles. After the methane production could no longer be detected, the reactors were sampled destructively to analyze the leachate. All of the experiments were carried out in duplicate, and the data presented in this paper are the averages based on two parallel experiments.

2.3. Analytical methods

2.3.1. Biochemical composition of materials

The TS and VS of the substrates were determined using Standard Methods APHA 2540G (APHA, 2005) by drying the biomass at 105 °C for 24 h and incineration at 550 °C for 2 h, respectively. Total Kjehdahl nitrogen (TKN) and ammonia nitrogen were measured using a Kjeltec 8400 Analyzer (Foss, Denmark). Organic nitrogen was calculated as TKN - ammonia nitrogen. Total protein was estimated by multiplying the organic nitrogen by 6.25. Lipids were measured by gravimetric analysis after diethyl ether-petroleum ether extraction. Cellulose, hemicellulose, and lignin analyses were determined using the Van Soest method (Van Soest and Wine, 1967; Van Soest, 1967).

2.3.2. Biogas and liquid characteristics

The composition of the biogas including methane and carbon dioxide, was determined using a gas chromatograph (GC9800, Guangzheng, China), equipped with a thermal conductive detector (TCD). The gas relative pressure in the bottles was measured with a differential pressure meter (TESTO 512, Germany), while the atmospheric pressure and temperature were measured with a Digital atmospheric pressure gauge (DYM3-02, YONGZHI, China). The volume of the methane and carbon dioxide generated during BMP were expressed as the Standard Temperature and Pressure (STP, 0 °C and 1 atm). The liquid samples were centrifuged at 16,000*g* for 15 min. The total carbon (TC), total organic carbon (TOC), and total inorganic carbon (TIC) content of the supernatant were analyzed using a TOC analyzer (TOC-V CPN, SHIMADZU, Japan).

Table 1
Basis for choosing representative biodegradable materials.[a]

Material	Note
Camphor tree branch	Dicotyledon, hardwood, used in roadside trees and home decoration
Camphor tree leaf	
Metasequoia branch	Gymnosperm, softwood, used in roadside trees and home decoration
Metasequoia leaf	
Bamboo branch	Monocotyledon, used in the garden and making chopsticks, and China is the world's most main bamboo production country
Bamboo leaf	
Reed	Monocotyledon, used in wet land
Cynodon dactyton	Monocotyledon, used in courtyard
Celery	One of the main vegetables
Lettuce	One of the main vegetables
Peanut shell	Ranking first in Chinese Oil Crops in 2008, nut waste
Grapefruit peel	Seasonal fruit
Watermelon peel	Ranking first in Chinese Fruits Yield in 2008
Apple core and peel	Ranking second in Chinese Fruits Yield in 2008
Orange peel	Ranking third in Chinese Fruits Yield in 2008
Banana peel	Ranking sixth in Chinese Fruits Yield in 2008
Tea residue	Chinese tea production is 1.26 million tons, accounting for 34.5% of global production
Sugarcane residue	Monocotyledon, ranking second in Chinese Sugar Crops Yield in 2008
Potato	High starch content
Soybean	High protein content, ranking fourth in Chinese Grain Crops Yield in 2008
Cotton	High cellulose content, ranking tenth in Chinese Farm Crops Yield in 2008
Fabric	Grouped alone in solid waste classification
Fat pork	Ranking first in Chinese Meats Yield in 2008
Lean pork	
Pig bone	
Fish bone	Ranking first in Chinese Aquatic Products Yield in 2008
Toilet paper	The maximum paper in Chinese landfill
Office paper	Low lignin content
Bleached newspaper	High lignin content

[a] *Source:* (China NBS, 2009; Shanghai Environmental Engineering Design and Science Academy, 2009; Barlaz, 1998).

2.4. Data analysis

2.4.1. Calculation of methane yield, L_0

Since some materials still have low methane production at the end of BMP tests, the final methane production potential needs to be predicted from kinetic model. First-order decay kinetics is widely used for landfill decay model, e.g., IPCC model (IPCC, 2006). However, the L_0 value calculated using first-order kinetics model with a lag phase showed that a first-order kinetics model was not appropriate ($R^2 < 0$). Thus, a cumulative methane production data derived from the experiments were fitted to a modified Gompertz equation (Lay et al., 1996). The modified Gompertz equation is:

$$V_{CH_4} = L_0 \times \exp\left\{-\exp\left[\frac{R_m \times e}{L_0}(t_{lag} - t) + 1\right]\right\} \quad (1)$$

where V_{CH_4} is the cumulative methane production at time t (ml CH_4 (STP) g VS^{-1}), L_0 is the methane yield potential (ml CH_4 (STP) g VS^{-1}), R_m is the maximum methane production rate (ml CH_4 (STP) d^{-1} g VS^{-1}), e is the mathematical constant (=3.1415926), t_{lag} is the duration of the lag phase (d), and t is the duration of the assay of cumulative methane production (d).

2.4.2. Calculation of the first order anaerobic decay rate, k

Eq. (2), which was developed by Cruz and Barlaz (2010), was used to estimate the anaerobic decay rate. This equation assumes no lag time and is based on the reactive mass of carbon, rather than the total mass:

$$\ln[m_0 - (m_{CH_4} + m_{CO_2})] = -kt + \ln(m_0) \quad (2)$$

where m_0 is the initial reactive mass of C in the substrates (g), CH_4 is the mass of C for the methane yield at that time (g), and CO_2 is the mass of C for the carbon dioxide yield at that time (g). The first-order decay constant (k) was estimated by linear regression.

2.4.3. Calculation of the carbon sequestration factor CSF

The CSF described by Barlaz (1998) for each component was used to express the mass of carbon stored per initial dry mass of component. The mass balance was used to calculate the CSF with the following equation:

$$CSF = \frac{m_0 - (m_{CH_4} + m_{CO_2} + m_1)}{M} \quad (3)$$

where m_1 is the carbon mass dissolved in the liquid (g) and M is the initial dry mass of component (g).

2.4.4. Statistical method

Parameters including L_0, t_{lag}, R_m, and k were determined using OriginLab (OriginLab Co., USA) and minimum variance regression fitting. To assess the relationship between the anaerobic degradation parameters and the biodegradable solid waste compositions, we applied hierarchical cluster analysis to the anaerobic degradation parameters using PASW Statistics 18 (SPSS Co. Ltd., USA) based on the squared Euclidean distance and within-groups linkage.

3. Results and discussion

3.1. Biochemical characterization

The methane yield of an anaerobic process depends on the amount of organics (represented by VS content) and the biochemical characteristics of the organics (Buffiere et al., 2006). Therefore, it is necessary to distinguish the biochemical characteristics of the organics. Table 2 shows overviews of the VS values and macromolecular composition (including protein, lipids and lignocellulose), respectively. It should be noted that the nitrogen content of fabric could not be determined using the aforementioned analytical methods because the fabrics contained many dyes. Dye significantly affect the colorimetric techniques used for TKN

Table 2
Biochemical characteristics of materials.

Material	VS (g g TS)	Protein (g g TS)	Lipid (g g TS)	Hemicellulose (g g TS)	Cellulose (g g TS)	Lignin (g g TS)
Camphor tree branch	0.968 (0.004)[a]	0.018 (0.004)	0.028 (0.011)	0.187 (0.001)	0.426 (0.016)	0.205 (0.007)
Camphor tree leaf	0.917 (0.002)	0.093 (0.005)	0.060 (0.023)	0.175 (0.003)	0.188 (0.002)	0.201 (0.002)
Metasequoia branch	0.963 (0.005)	0.033 (0.004)	0.032 (0.012)	0.126 (0.001)	0.349 (0.008)	0.337 (0.005)
Metasequoia leaf	0.917 (0.007)	0.113 (0.001)	0.090 (0.039)	0.121 (0.004)	0.113 (0.006)	0.108 (0.002)
Bamboo branch	0.973 (0.002)	0.010 (0.001)	0.006 (0.001)	0.262 (0.004)	0.426 (0.003)	0.168 (0.005)
Bamboo leaf	0.869 (0.004)	0.140 (0.001)	0.044 (0.001)	0.386 (0.004)	0.258 (0.001)	0.050 (0.005)
Reed	0.934 (0.006)	0.061 (0.003)	0.011 (0.001)	0.330 (0.008)	0.381 (0.002)	0.090 (0.001)
Cynodon dactyton	0.912 (0.002)	0.090 (0.001)	0.030 (0.001)	0.465 (0.001)	0.286 (0.004)	0.061 (0.002)
Celery	0.738 (0.002)	0.197 (0.002)	0.063 (0.022)	0.110 (0.010)	0.237 (0.003)	0.042 (0.005)
Lettuce	0.816 (0.005)	0.299 (0.002)	0.070 (0.008)	0.129 (0.005)	0.149 (0.004)	0.041 (0.009)
Peanut shell	0.970 (0.002)	0.047 (0.002)	0.006 (0.001)	0.129 (0.001)	0.400 (0.003)	0.338 (0.003)
Grapefruit peel	0.958 (0.014)	0.073 (0.002)	0.010 (0.001)	0.048 (0.001)	0.161 (0.007)	0.008 (0.004)
Watermelon peel	0.823 (0.010)	0.276 (0.005)	0.055 (0.027)	0.118 (0.011)	0.265 (0.012)	0.033 (0.013)
Apple core and peel	0.985 (0.005)	0.035 (0.001)	0.030 (0.002)	0.029 (0.002)	0.075 (0.002)	0.017 (0.004)
Orange peel	0.999 (0.001)	0.048 (0.004)	0.013 (0.001)	0.034 (0.002)	0.119 (0.009)	0.002 (0.001)
Banana peel	0.838 (0.024)	0.091 (0.003)	0.086 (0.029)	0.174 (0.007)	0.190 (0.001)	0.116 (0.012)
Tea residue	0.965 (0.001)	0.239 (0.001)	0.038 (0.001)	0.336 (0.001)	0.152 (0.001)	0.113 (0.001)
Sugarcane residue	0.966 (0.004)	0.034 (0.001)	0.035 (0.018)	0.211 (0.002)	0.279 (0.002)	0.045 (0.001)
Potato	0.956 (0.001)	0.087 (0.001)	0.002 (0.001)	0.452 (0.009)	0.025 (0.002)	0.005 (0.001)
Soybean	0.945 (0.001)	0.359 (0.006)	0.232 (0.032)	0.040 (0.002)	0.064 (0.002)	0.000 (0.000)
Cotton	0.983 (0.003)	0.015 (0.001)	0.004 (0.001)	0.013 (0.007)	0.965 (0.001)	0.000 (0.000)
Fabric	0.999 (0.001)	na[b]	na	na	na	na
Fat pork	0.998 (0.001)	0.028 (0.003)	0.996 (0.001)	na	na	na
Lean pork	0.995 (0.001)	0.801 (0.033)	0.074 (0.001)	na	na	na
Pig bone	0.534 (0.006)	0.478 (0.007)	0.422 (0.014)	na	na	na
Fish bone	0.447 (0.009)	0.619 (0.008)	0.196 (0.003)	na	na	na
Toilet	0.993 (0.004)	0.003 (0.001)	0.256 (0.001)	0.101 (0.005)	0.848 (0.007)	0.042 (0.012)
Office paper	0.807 (0.006)	0.006 (0.001)	0.004 (0.001)	0.108 (0.003)	0.796 (0.006)	0.000 (0.000)
Bleached newspaper	0.915 (0.002)	0.007 (0.001)	0.008 (0.001)	0.112 (0.001)	0.662 (0.009)	0.166 (0.016)

[a] Data range was presented parenthetically.
[b] na = Not applicable.

determination. Therefore, the protein analytical method was not applicable to fabric. Based on the product description, the fabrics used in this study contained wool (25 wt%), acrylic fiber (70%), and polyurethane fiber (5%). All of the materials that originated from animals and fabrics lacked lignocellulose.

As shown in Table 2, fish bone and pig bone contained >40% inorganic compounds. The VS of bamboo leaf, celery, lettuce, watermelon peel, banana peel, and office paper were about 80%. The VS contents of other materials were >90%. As shown in Table 2, fat pork had the highest lipid content, followed by pig bone and soybean. All of the animal materials except fat pork contained high protein, larger than 0.40 g g VS^{-1}. The highest protein content in the plant materials was found in soybean, about 0.36 g g VS^{-1}. Cotton had the highest cellulose content, about 0.97 g g VS^{-1}. Metasequoia branch, which is a type of softwood, and peanut shell, which is a nut waste, had the highest lignin content, with about 0.33 g g VS^{-1}.

3.2. Anaerobic degradation parameters

The anaerobic degradation parameters, i.e., L_0, t_{lag}, R_m, k, and CSF, for each material are shown in Table 3. The fitting curves for L_0 and k were shown in Appendices. All of the parameters were corrected by subtracting the effect of the inoculum.

3.2.1. Classification method based on the methane yield potential

The anaerobic decomposition of solid waste in landfill leads to the generation of the greenhouse gases methane and carbon dioxide. The greenhouse effect of methane is 24 times higher than that of carbon dioxide (IPCC, 2007a,b). Methane is also a combustible gas and can be used to generate thermal energy. Therefore, methane production data for landfills are essential for evaluating the effects of landfill on global climate change and for landfill management strategies. The hierarchical cluster analysis of the methane yield potential is shown in Fig. 1, which indicates that the biodegradable materials could be divided into five categories.

The first category comprised apple core and peel, orange peel, grapefruit peel, watermelon peel, sugarcane residue, celery, lettuce, potato, office paper, and toilet paper. Thus, the first category mainly comprised fruit and vegetable materials where the L_0 value range was 253–337 ml CH_4 g VS^{-1}. Office paper and toilet paper with high methane yields of 300 and 294 ml CH_4 g VS^{-1}, respectively, also belonged to the first category because of their low lignin contents.

The second category comprised grass and leaves, including *Cynodon dactylon*, reed, bamboo leaf, camphor tree leaf, tea residues, and metasequoia leaves where the L_0 value range was 118–219 ml CH_4 g VS^{-1}. Banana peel had a L_0 value of 227 ml CH_4 g VS^{-1}, so it was suggested to be classified into the first category, because it was a fruit/vegetable material and its L_0 value was the highest in the second category but nearest to the first category. The L_0 value of bleached newspaper was similar to those of grass and leaves, about 181 ml CH_4 g VS^{-1}, which was about 2.4 times the value (75 ml CH_4 g VS^{-1}) reported by Eleazar et al. (1997). This difference was explained by differences in the lignin contents of the paper tested. The lignin contents of the paper used in this study and in the study of Eleazar et al. were 0.17 and 0.24 g g VS^{-1}, respectively. Furthermore, we only used the bleached newspaper without ink whereas the total newspaper was used by Eleazar et al. (1997). Cummings and Stewart (1994) showed that cellulose fiber covered by ink had a reduced bioavailability, although the newsprint ink itself was not toxic. The L_0 values of coated paper and corrugated cardboard reported by Eleazar et al. (1997) were similar to the L_0 value for bleached newspaper detected in the present study because they had the same lignin content of around 0.20 g g VS^{-1}. Therefore, all types of paper with a lignin content >0.15 g g VS^{-1} can be grouped into one category.

Table 3
Landfilling degradation parameters.

	L_0 (ml CH_4 g VS^{-1})[a]	t_{lag} (d)[a]	R_m (ml CH_4 d^{-1} g VS^{-1})[a]	R_1^2[b]	k ($10^{-3} \times d^{-1}$)[a]	R_2^2[c]	CSF (g C g TS^{-1})[d]
Camphor tree branch	129.8 (1.4)	5.4 (0.4)	3.9 (0.1)	0.998	5.9 (0.4)	0.962	0.334 (0.017)
Camphor tree leaf	155.3 (3.3)	7.6 (0.5)	11.6 (0.9)	0.993	19.6 (1.8)	0.960	0.294 (0.010)
Metasequoia branch	46.6 (0.8)	2.8 (0.7)	2.5 (0.2)	0.991	2.0 (0.4)	0.859	0.390 (0.001)
Metasequoia leaf	118.1 (2.4)	6.3 (0.5)	7.2 (0.5)	0.996	9.0 (0.9)	0.952	0.333 (0.017)
Bamboo branch	65.3 (1.1)	22 (0.9)	2.2 (0.1)	0.991	2.6 (0.2)	0.964	0.409 (0.006)
Bamboo leaf	204.2 (5.5)	na[e]	4.8 (0.4)	0.973	7.0 (0.4)	0.956	0.215 (0.003)
Reed	184.0 (2.6)	4.1 (0.6)	7.0 (0.3)	0.993	13.3 (0.5)	0.983	0.246 (0.005)
Cynodon dactyton	218.7 (6.2)	2.5 (1.1)	6.8 (0.5)	0.982	11.1 (0.5)	0.975	0.237 (0.003)
Celery	253.0 (3.2)	11.5 (0.3)	24.2 (1.3)	0.997	51.0 (4.4)	0.965	0.105 (0.011)
Lettuce	294.1 (4.5)	9.9 (0.3)	31.4 (2.1)	0.992	52.9 (3.7)	0.961	0.127 (0.062)
Peanut shell	31.6 (1.1)	5.1 (1.0)	1.7 (0.2)	0.987	1.5 (0.2)	0.950	0.457 (0.002)
Grapefruit peel	276.1 (8.3)	15 (0.6)	30.8 (4.0)	0.977	33.4 (4.5)	0.841	0.057 (0.002)
Watermelon peel	265.5 (3.1)	11.0 (0.2)	25.3 (1.1)	0.998	42.0 (3.4)	0.964	0.118 (0.048)
Apple core and peel	276.7 (11.1)	14.4 (0.8)	16.8 (2.0)	0.982	30.4 (0.2)	0.962	0.089 (0.005)
Orange peel	276.8 (7.5)	17.6 (0.6)	18.4 (1.6)	0.990	32.2 (2.7)	0.942	0.052 (0.018)
Banana peel	227.1 (4.1)	14.0 (0.3)	30.7 (2.6)	0.993	59.0 (6.0)	0.952	0.159 (0.007)
Tea residue	160.1 (5)	10.1 (0.8)	14.3 (2.1)	0.979	12.6 (2.0)	0.846	0.303 (0.001)
Sugarcane residue	253.0 (6.9)	11.9 (1.2)	8.5 (0.8)	0.975	14.9 (0.7)	0.964	0.144 (0.006)
Potato	336.6 (6.4)	13.2 (0.5)	37.1 (3.6)	0.991	84.0 (7.7)	0.936	0.008 (0.008)
Soybean	443.9 (5.1)	12.7 (0.2)	29.8 (0.9)	0.998	51.8 (1.9)	0.981	0.106 (0.039)
Cotton	421.4 (9.9)	9.7 (0.3)	17.1 (0.5)	0.996	116.0 (5.7)	0.960	0.019 (0.011)
Fabric	36.2 (3.1)	10.0 (1.8)	1.9 (0.4)	0.965	1.3 (0.1)	0.996	0.556 (0.003)
Fat pork	971.0 (7.6)	19.7 (0.2)	50.4 (1.0)	0.998	77.3 (3.9)	0.949	0.119 (0.002)
Lean pork	426.7 (6.2)	6.6 (0.2)	30.0 (1.0)	0.995	51.8 (1.0)	0.995	0.022 (0.004)
Pig bone	408.2 (3.5)	10.7 (0.2)	36.7 (1.1)	0.999	55.2 (2.6)	0.983	0.088 (0.003)
Fish bone	194.0 (4.5)	9.8 (0.5)	24.3 (3.2)	0.986	19.3 (4.1)	0.810	0.134 (0.001)
Toilet paper	294.3 (11.8)	26.1 (1.1)	18.3 (2.8)	0.977	42.9 (3.1)	0.955	0.074 (0.001)
Office paper	299.9 (8.1)	9.5 (0.6)	22.6 (2.0)	0.986	50.0 (3.6)	0.957	0.066 (0.002)
Bleached newspaper	180.9 (5.2)	12.2 (0.7)	14.3 (1.6)	0.990	25.4 (2.3)	0.961	0.205 (0.012)

[a] Data represented the fitted values using Eq. (1). Curve-fitting utilized the averages for two parallel reactors. Standard error was presented parenthetically.

[b] R square was obtained from fitting Eq. (1).

[c] R square represented goodness of fit for Eq. (2).

[d] Carbon sequestration factor (CSF) calculated from Eq. (3) was the average of duplicates and data range was below.

[e] na = not applicable, the fitted value was negative. The BMP tests results were well fitted by Modified Gompertz model for L_0 ($R^2 \geqslant 0.965$) and first order kinetic model for k ($R^2 \geqslant 0.805$).

The third category comprised metasequoia branch, bamboo branch, peanut shell, and fabric where L_0 value range was 32–65 ml CH_4 g VS^{-1}. In particular, the branches of camphor trees, a type of hardwood dicotyledon, had a L_0 value of 130 ml CH_4 g VS^{-1}, which was classified into the second category, whereas the branches of metasequoia, a type of softwood gymnosperm, had a low L_0 value of 47 ml CH_4 g VS^{-1} so it was classified into the third category. Wang et al. (2011) indicated that the L_0 of red oak (a hardwood) was higher than that of spruce and radiata pine (two types of softwood), whereas the L_0 of eucalyptus (a tropical hardwood) was nearly zero. Wang et al. (2011) explained that eucalyptus had toxic effects that inhibited methane production. However, the lignin contents of tropical hardwoods can exceed the lignin contents of many softwoods. Thus, even without their toxic effect, the L_0 of tropical hardwood is not necessarily higher than that of softwood. In general, it was difficult to distinguish softwood and hardwood based on their methane yield potentials.

The fourth category comprised pig bone, lean pork, soybean, and cotton where L_0 value range was 408–444 ml CH_4 g VS^{-1}. Staley and Barlaz (2009) suggested that the L_0 of cotton was similar to office paper according to the knowledge of researchers. By contrast, the present study confirmed that the L_0 values of cotton and office paper were 421 ml CH_4 g VS^{-1} and 300 ml CH_4 g VS^{-1}, respectively. Thus, the L_0 of cotton was significantly higher than that of office paper. The total hemicellulose and cellulose contents of cotton and office paper were >0.9 g g VS^{-1}, and no lignin was detected. However, the hemicellulose contents of cotton and office paper were 0.01 g g VS^{-1} and 0.11 g g VS^{-1}, respectively. Hemicellulose can hinder cellulose degradation (Sun and Cheng, 2002). In addition, differences in the crystallinity of cotton and office paper could lead to different L_0 values (Fan and Lee, 1983). The L_0 of pig bone and lean pork, two types of animal-derived food material, were 408 ml CH_4 g VS^{-1} and 427 ml CH_4 g VS^{-1}, respectively. Fish bone, which belongs to the second category, was also a kind of animal-derived food waste, but only had a L_0 value of 194 ml CH_4 g VS^{-1}, even smaller than fruit and vegetable waste. The main biochemical composition of fish bone was protein as shown in Table 2. The protein type of fish bone is mainly consisted collagens (Takeshi and Nobutaka, 2000). This type of protein maybe resistant to anaerobic degradation than other proteins. The L_0 value of fish bone was quite different from other animal-derived food waste, so the L_0 of animal-derived food waste for area where fish is the main food should be much lower. The L_0 of soybean, which had a high protein and lipid content, was 444 ml CH_4 g VS^{-1}. Soybean is hard to get into landfill. The reason to choose soybean as a material is that it is rich in vegetable protein.

The fifth category comprised fat pork with a L_0 value of 971 ml CH_4 g VS^{-1}. Fat pork had the highest L_0 value because of its high lipid content (0.99 g g VS^{-1}). The theoretical L_0 of lipid, which was 1014 ml CH_4 g VS^{-1} (Angelidaki and Sanders, 2004), was similar to the L_0 of fat pork in the present study. Fat pork is hard to get into landfill. the reason to choose fat pork as a material is that it is rich in animal lipid. But the L_0 of animal-derived food waste which contains high lipid content should be much higher.

Overall, the L_0 of animal-derived food waste was higher than that of plant-derived food waste. Thus, based on the methane yield potential, it was reasonable to divide organic waste into animal-derived and plant-derived organic waste, as described in the Chinese MSW Sampling Standard Method (Chinese Construction Ministry, 1995). There are different dietary habits in countries and regions so the different L_0 values of food waste should be determined. In summary, based on the methane yield potential,

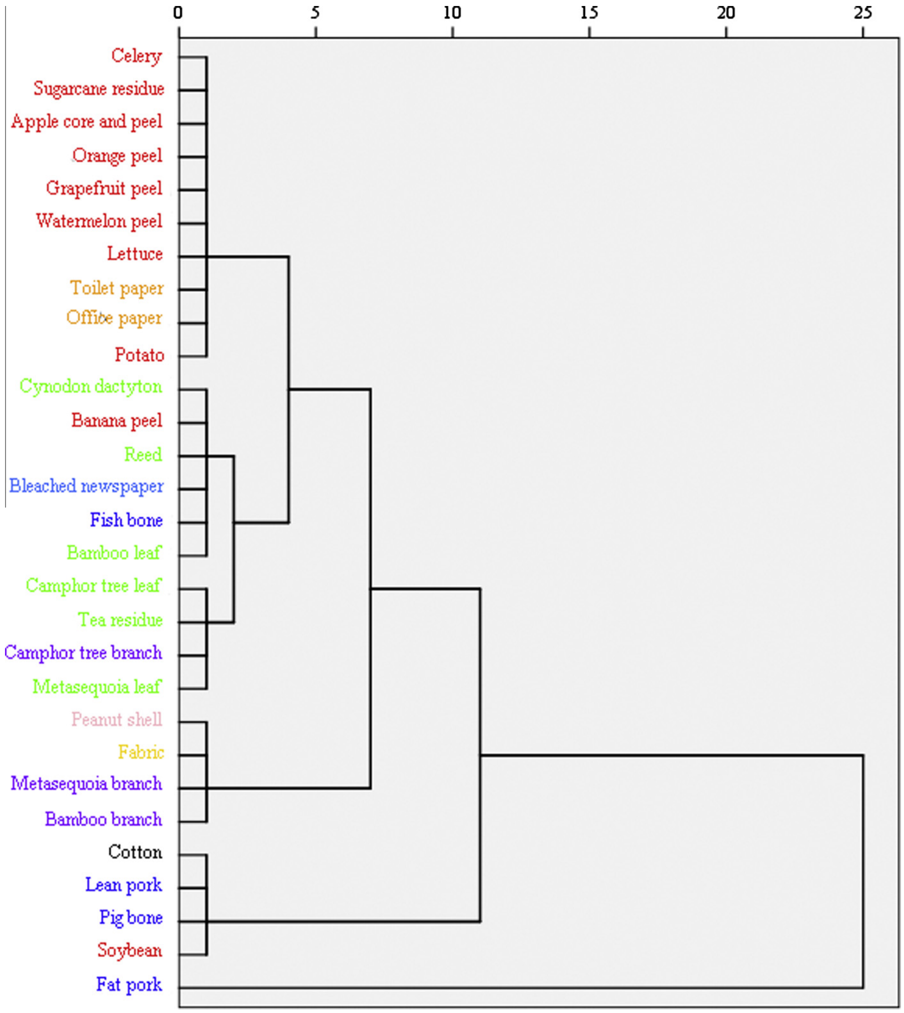

Fig. 1. Hierarchical cluster analysis of L_0. Red: fruit and vegetable waste; Blue: animal-derived food waste; Pink: nut waste; Orange: biodegradable paper; Cyan: refractory paper; Green: grass and leaves; Purple: wood; Yellow: fabric. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

waste can be divided into fruit and vegetable waste, animal-derived food waste, nut waste, biodegradable paper, refractory paper, grass and leaves, wood, and fabric.

3.2.2. Classification method based on the anaerobic decay rate

The k value determined by BMP tests cannot represent the actual status of landfill, but the k values can be compared to evaluate relative rate of degradation. The hierarchical cluster analysis of the anaerobic decay rate (Fig. 2) suggested that the materials could be classified into three clusters.

The first cluster comprised non-nut food waste, including soybean, potato, celery, lettuce, pig bone, fat pork, lean pork, banana peel, watermelon peel, apple core and peel, grapefruit peel, and orange peel where the k value range was $30.4–84.0 \times 10^{-3}\,d^{-1}$ while it also comprised biodegradable paper, including toilet paper and office paper with CSF values of $42.9 \times 10^{-3}\,d^{-1}$ and $50.0 \times 10^{-3}\,d^{-1}$, respectively. It was reasonable that food waste is easy for anaerobic degradation, as reported by Cruz and Barlaz (2010) and IPCC (2006). The second cluster comprised garden waste including metasequoia branch, bamboo branch, camphor tree branch, bamboo leaf, metasequoia leaf, camphor tree leaves, tea residues, reed and *Cynodon dactylon* where the k value range was $2.0–19.6 \times 10^{-3}\,d^{-1}$, while it also comprised fabric, peanut shells, sugarcane residue, fish bone and bleached newspaper with k values of $1.3 \times 10^{-3}\,d^{-1}$, $1.5 \times 10^{-3}\,d^{-1}$, $14.9 \times 10^{-3}\,d^{-1}$, $19.3 \times 10^{-3}\,d^{-1}$, and $25.4 \times 10^{-3}\,d^{-1}$, respectively. And the k of wood was smaller than grass and leaves waste. The k values range of wood was $2–5.9 \times 10^{-3}\,d^{-1}$ and the k values range of grass and leaves waste was $7–19.6 \times 10^{-3}\,d^{-1}$. The lignin content of wood was larger than that of grass and leaves waste, so the decay rates of wood were lower. Cruz and Barlaz (2010) showed that grass and leaves had higher decay rate than food waste. But Cruz and Barlaz themselves also pointed out that this result was less intuitive. And this result may be caused by inappropriate choice of degradation date for curve fitting. Sugarcane residue and fish bone belonged to non-nut food waste, but k values of sugarcane residue and fish bone were quite different from other non-nut food waste, so the k of non-nut food waste for area where the quantity of sugarcane residue and fish bone is large should be much lower. The third cluster contained cotton with k value of $116.0 \times 10^{-3}\,d^{-1}$. Since cotton has no lignin content, and the crystallinity of cotton is easy for anaerobic degradation.

In summary, based on the anaerobic decay rate, waste should be divided into non-nut food waste, nut waste, degradable paper, refractory paper, grass and leaves, wood, and fabric.

3.2.3. Classification method based on the carbon sequestration factor

The humic substances formed during the degradation of degradable solid waste can persist in landfill for a long time. A large amount of carbon is buried in landfill, which is a carbon sink

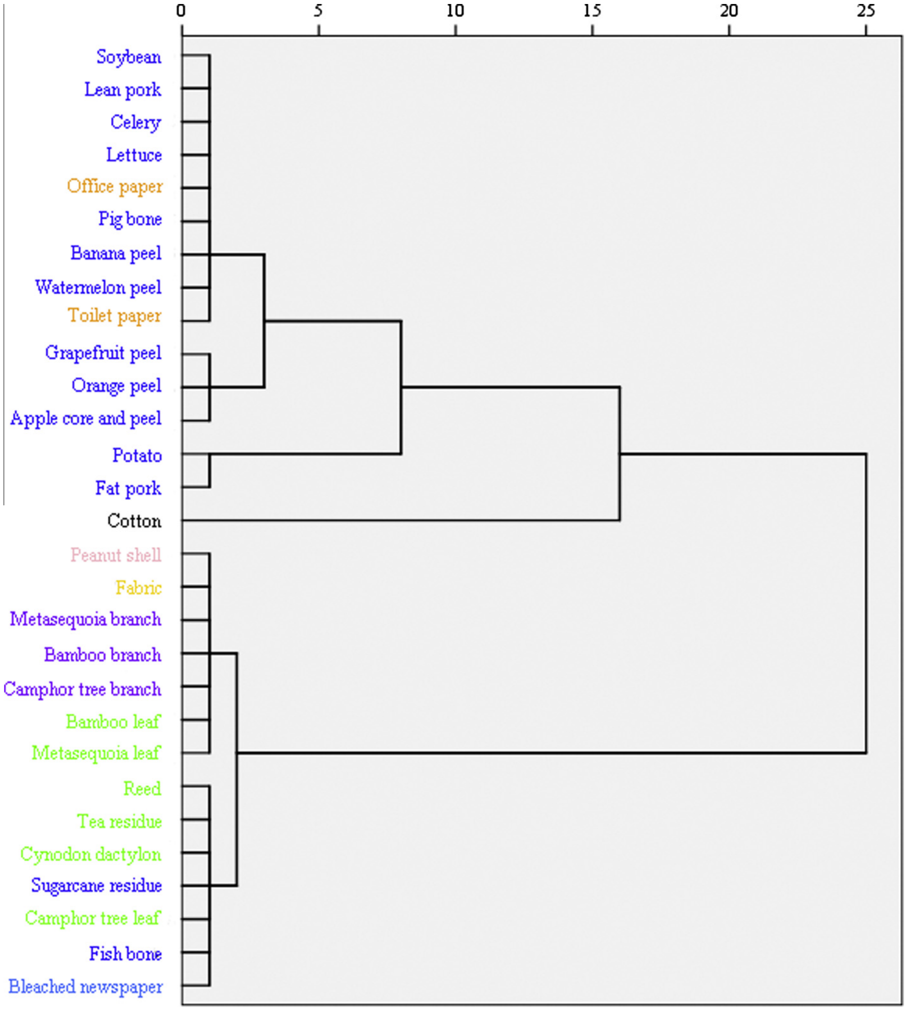

Fig. 2. Hierarchical cluster analysis of *k*. Blue: non-nut food waste; Pink: nut waste; Orange: degradable paper; Cyan: refractory paper; Green: grass and leaves; Purple: wood; Yellow: fabric. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

that eliminates carbon from the atmospheric environment. Therefore, CSF is a very important parameter for evaluating the landfill impact on climate change. The hierarchical cluster analysis of CSF (Fig. 3) suggested that the materials could be divided into four categories.

The first category comprised non-nut food waste, including fat pork, lean pork, pig bone, fish bone, watermelon peel, apple core and peel, grapefruit peel, orange peel, banana peel, sugarcane residue, potato, soybean, lettuce, and celery where the CSF value range was 0.022–0.159 g C g TS^{-1}. This category also included biodegradable paper such as toilet paper and office paper with CSF values of 0.074 g C g TS^{-1} and 0.066 g C g TS^{-1}, respectively. Since the recalcitrant carbon content such as lignin was low. Barlaz (1998) showed that CSF values of food waste and office paper are 0.08 and 0.05 g C g TS^{-1}, similar to this research. The second category contained grass and leaves, including reed, *Cynodon dactylon*, bamboo leaf, camphor tree leaf, metasequoia leaf, and tea residues where the CSF value range was 0.215–0.333 g C g TS^{-1}, while this category also included bleached newspaper with a CSF value of 0.205 g C g TS^{-1}. Camphor tree branches had a CSF value of 0.334 g C g TS^{-1}, it was suggested to be classified into the third category, because it was branches and its CSF value was the highest in the second category. The third category comprised metasequoia branches and bamboo branches where the CSF value range was 0.390–0.409 g C g TS^{-1}, while this category also included peanut shell with a CSF value of 0.457 g C g TS^{-1}. The lignin content in the third category materials was high, so the CSF value of this category was much higher. The fourth category comprised fabric with a *k* value of 0.556 g C g TS^{-1}. Since fabric contained acrylic fiber (70%) and polyurethane fiber (5%) which is recalcitrant in biodegradation process.

Thus, based on CSF, waste should be divided into non-nut food waste, nut waste, degradable paper, refractory paper, grass and leaves, wood, and fabric.

3.3. Demand for different waste classification features

The present study subdivided food waste into nut waste, non-nut plant-derived food waste, and animal-derived food waste based on L_0. However, based on CSF, food waste was subdivided into nut waste and non-nut food waste. This was because the lipid content of animal-derived food waste was far higher than that of plant-derived food waste. The lignin content of non-nut plant-derived food waste was also <5%. A high lipid content produced high L_0 values whereas a low lignin content led to relatively complete degradation and a low CSF value.

In previous studies, paper was subdivided into office paper, coated paper, newspaper and corrugated cardboard (Barlaz, 1998; Cruz and Barlaz, 2010; Eleazar et al., 1997; Wang et al., 2011). However, in the present study, paper was subdivided only into refractory paper and degradable paper. Refractory paper includes newspaper, coated paper and corrugated cardboard with a

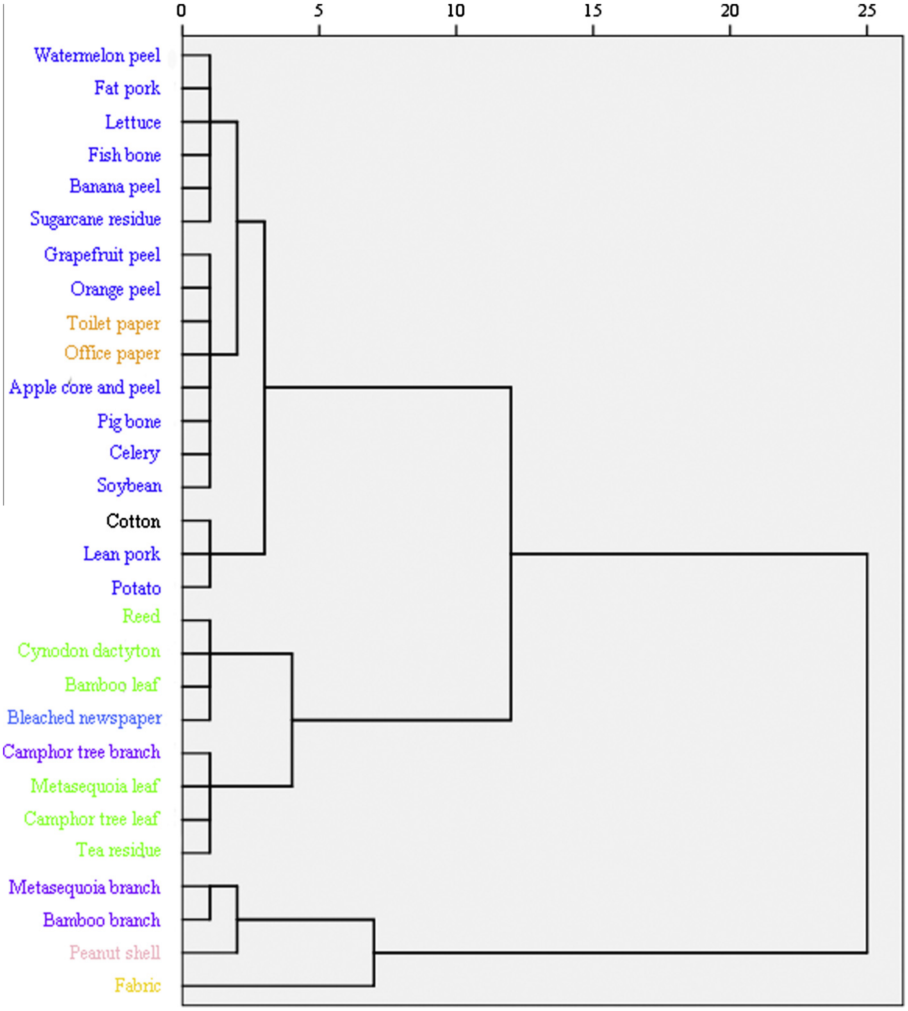

Fig. 3. Hierarchical cluster analysis of CSF. Blue: non-nut food waste; Pink: nut waste; Orange: degradable paper; Cyan: refractory paper; Green: grass and leaves; Purple: wood; Yellow: fabric. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

lignin content >0.15 g g VS^{-1}, whereas biodegradable paper comprises office paper and toilet paper with a lignin content <0.05 g g VS^{-1}. The lignin content of newspaper used in previous studies was higher than that of coated paper and corrugated cardboard. In the present study, however, the lignin content of bleached newspaper was lower than that of coated paper and corrugated cardboard. Thus, it is difficult to distinguish the anaerobic degradation parameters of newspaper, coated paper, and corrugated cardboard.

In this study, garden waste was subdivided into branches, grass, and leaves. The L_0, k, and CSF values of leaves were similar to those of grass, mainly because they had similar biochemical characteristics. The lignin contents of branches, and grass and leaves were >10% and <10% (except camphor tree leaf), respectively. Lignin inhibits cellulose degradation. Therefore, the L_0, k, and CSF values of grass and leaves were similar. The L_0 and k values of grass and leaves were higher than those of branches, while the CSF values of grass and leaves were lower than that of branches.

Wood should not be subdivided because the lignin content of hardwood and softwood overlaps.

4. Conclusion

We studied the biochemical characteristics and anaerobic degradation parameters of 29 different materials. To calculate the anaerobic degradation parameters more accurately, we propose to improve the MSW classification method based on our cluster analysis results, as follows:

1. Food waste should be subdivided into nut waste, non-nut plant-derived food waste, and animal-derived food waste when calculating the L_0. However, food waste should only be subdivided into two categories when determining the CSF: nut waste and non-nut food waste.
2. Paper should be subdivided into refractory paper and degradable paper. Refractory paper includes newspaper, coated paper and corrugated cardboard. Degradable paper includes office paper and toilet paper.
3. Garden waste should be divided into grass and leaves, and branches. The L_0, k, and CSF values of leaves are similar to those of grass.
4. Wood should not be subdivided when calculating the CSF.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.wasman.2013.08.015.

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