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Quantitative evaluation of heavy metals' pollution hazards and estimation of heavy metals' environmental costs in leachate during food waste composting

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ABSTRACT

Heavy metals in leachate during food waste composting may produce different degrees of pollution hazards and further induce environment costs, when the concentrations of heavy metals exceed the discharging quality standards. Quantitative evaluation of heavy metals' pollution hazards and estimation of such environmental costs are under-represented in the existing literature. This paper uses a logistic function approach to evaluate the extent of pollution hazards of heavy metals such as cadmium (*Cd*), chromium (*Cr*), mercury (*Hg*), lead (*Pb*) and arsenic (*As*) and to estimate heavy metals' environmental costs in leachate during food waste composting from Minhang food waste treatment plant located in northern Shanghai, China. Major findings of this study are: (1) The pollution hazards rate of *Cd* amounts to 94.03%, probably because *Cd*-containing materials such as plastics are mixed with food waste; (2) With the comprehensive pollution hazards rate estimated as 94.48%, the environmental costs caused by heavy metals in leachate during food waste composting amount to US$0.52 per tonne. This magnitude of environmental costs is meaningful and significant, considering that it is equivalent to 2.97% of Shanghai's food waste treatment charges.

1. Introduction

Food waste composting is widely used in some developing countries. This type of waste treatment can produce large amounts of leachate with various kinds of heavy metals (Soobhany et al., 2015; Genevini et al., 1997; Richard, 1992; Lopes et al., 2011; Moller and Schultheiss, 2015). Food waste includes not only food residues such as rice, bread, and vegetables, but also some materials associated with food consumption such as toothpicks, waste tableware, paper towels, plastics and so on (Yu et al., 2018; Maragkaki et al., 2017). These materials may contain a small amount of heavy metals (Manfredi et al., 2010). For example, plastics mainly contain cadmium, chromium, and lead (Huerta-Pujol et al., 2010). Pollution hazards of some heavy metals could be acute due to the serious toxicity that is present even in low concentrations (Christensen et al., 1999, 2000; Guertin, 2004; Jarup, 2003; Ko, 2004), which may entail substantial treatment costs. Governments across different countries have been financially stressed to deal with these problems (Lange and Nahman, 2015; Chen, 2016; Folz and Giles, 2002). In order to attenuate the treatment costs of some heavy metals, many researchers think that it is necessary to ascertain the degree of heavy metals' pollution hazards generated from the processing of several heavy metals (Huang et al., 2011; European Commission, 2008; Singh et al., 2015; Li et al., 2009).

Charging for food waste treatment on the basis of the polluter-pays principle is widely accepted as the way to mitigate financial stress of dealing with the problems (OECD, 1992). The environmental costs are also receiving increasing concerns because of the imposition of stricter pollutant discharging quality standards (Nahman, 2011; Slaper and Hall, 2011; Maalouf and El-Fadel, 2017; Kinnaman, 2014). However, the environmental costs caused by heavy metals in leachate during food waste composting have not been widely studied in the existing literature. This paper attempts to fill that gap in the literature by quantitatively evaluating heavy metals' pollution hazards in other water environments and computing the associated environmental costs in waste treatment, using a logistic function approach.

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The majority of previous studies focus on assessing heavy metals' pollution hazards in some water environments as a result of the heavy metals' serious toxicity (Cheng et al., 2013; Huang et al., 2011; Azizi et al., 2015; Kucuksezgin et al., 2006). For example, Cheng et al. (2013) determine the health hazards of heavy metals (*Cr, Pb, Cr, Cu, Ni, Zn, Fe* and *Mn*) in the aquaculture pond ecosystem of Pearl River Delta, China through a human health risk assessment approach. Huang et al. (2011) adopt Geo-accumulation index approach and Potential ecological risk index approach to evaluate the extent of pollution from heavy metals (*Pb, Zn, Cu, Cd, Cr* and *Ni*) presence in liquefaction residues of sewage sludge. These papers have not studied the water environment that is made up of leachate per se. Some scholars have discussed the concentration variation of heavy metals in leachate during the treatment process of municipal solid waste (MSW) landfill, but their study is carried out more from an experimental perspective rather than concrete quantitative evaluation (Li et al., 2009).

One factor leading to different estimates of the environmental costs caused by leachate in waste disposal is whether and how much the treatment conforms to wastewater discharging standard. Several studies use a contingent valuations (CV) approach to determine external costs (environment costs and social costs) of MSW by asking interviewees how much they would be willing to pay to avoid drinking water polluted by leachate (COWI, 2000; DEFRA, 2003; Ofiara, 2001). But the limitation of this CV method lies in the absence of quantitative information associated with health impacts, and many researchers hold that environment costs are not worth considering if a landfill abides by current regulations (Rabl et al., 2008). Additionally, Nahman (2011) assumes that external costs of MSW is determined in accordance with international standards. While these studies attempt to quantify the external costs about leachate, they restrict its usage in food waste composting. And when referring to the environmental costs under this waste disposal technique, some current studies primarily focus on the overall environmental costs induced by carbon or nutrient substance such as oxygen demand (BOD), chemical oxygen demand suspended solids (SS), and other nutrients, instead of computing the environmental costs caused by heavy metals in leachate under the condition of the discharging standard being violated (Maalouf and El-Fadel, 2017; Chen, 2016; Xu and Liu, 2013).

In sum, quantitative evaluation of heavy metals' pollution hazards and estimation of environment costs in leachate during food waste composting are under-studied in the past research. To counter the lack of literature in this area, this study outlines a logistic function approach to determine the degree of pollution hazards and per tonne environmental costs associated with heavy metals (*Cd, Cr, Hg, Pb* and *As*) from Minhang food waste treatment plant located in northern Shanghai, China. Specifically, this study calculates the pollution hazards rate of each heavy metal and the comprehensive pollution hazards rate of these heavy metals together. The environmental costs are then estimated by computing the per tonne environmental costs under different comprehensive pollution hazards rates.

2. Data and methods

2.1. Definitions of food waste

This section explains the terminology employed in the study. According to "Shanghai Food Waste Disposal Management Measures" (Municipal Order 98), food waste refers to residual food and the waste of food processing, produced by catering services, workplace canteens, and food waste processing avenues, etc. What needs to be emphasized is that food waste in Shanghai is excluded in daily activities of residents. The main ingredients of food waste include food residues such as rice, wheat, vegetables, fish bones, meat bones, shellfish, oil, etc. and some materials associated with food consumption such as toothpicks, waste tableware, paper towels, plastics and so on (Yu et al., 2018).

2.2. Study area

The Minhang food waste treatment plant is situated in Minhang area which has a population of 2.54 million at the end of 2010 and an area of 370.75 square kilometers in the northern part of Shanghai, China. Minhang food waste treatment plant is the largest food waste disposal plant, processing 146 tonnes / day and the disposal quantities of food waste in this plant account for 17.89% of the total disposal quantities in Shanghai (Shanghai Greening and Municipal Management Bureau, 2013). Additionally, Minhang food waste treatment plant uses the composting disposal approach. Under the composting treatment technology, heavy metals are enriched in leachate during food waste composting treatment (SIDRE, 2014). Therefore, Minhang food waste treatment plant is selected as the research object.

2.3. Data

The diverse levels and various types of heavy metals were generally carried in leachate of food waste in different areas due to different living standards and living habits (Padeyanda et al., 2016). According to China's Twelfth Five-Year Plan, *Cd, Cr, Hg, Pb* and *As* were used as indicators for food waste management (CPGPRC, 2011). Hence, *Cd, Cr, Hg, Pb* and *As are selected* as the indicators for this study.

The main data in the study, the concentrations of heavy metals in leachate produced by Minhang food waste treatment plant, was obtained from The Special Report on Heavy Metals of Waste (SIDRE, 2014). This heavy metal report project measured the concentrations of *Hg, As, Cd, Cr* and *Pb* in leachate during food waste composting process. The survey was conducted one time in each quarter, respectively in March, May, July, October, during 2014. Two samples of the survey objects were collected each time using a quartering method (Morselli et al., 2010). Each sample was tested two times. This study used the average value of test results (a total of four times), and the outliers (numbers that deviate from the other values in the same group) were removed from calculation of the average value. Table 1 displays the concentration of heavy metals in leachate during food waste composting in March, May, July, and October respectively, with the bottom row showing the average concentration value of the above months. The data in Table 1 form the basis of subsequent calculations of pollution rates and environmental costs. The whole process of this project conformed to national standards.

Other data used in this paper are as follows. The amount of food waste from 2014 to 2020 was obtained from Ying et al. (2015). In compliance with The Special Report on Heavy Metals of Waste (SIDRE, 2014), one tonne of food waste was set to produce 0.33 tonnes of the leachate. The exchange rate in 2018 was 1 US Dollar for about 6.5521 RMB yuan (PBOC, 2018). The water price in Shanghai was 3.62 yuan / tonne (US$0.55 per tonne) in 2018. It was raised to 5 yuan / tonne (US$0.76 per tonne) in 2015 aiming to save water through price leveraging. To maintain data comparability, this paper assumes that the unit price of water from 2015 to 2020 stays constant, namely, 5 yuan / tonne (SMDRC, 2014).

2.4. The modeling of water pollution hazards

Economists James and Lee put forth a pollution-concentration curve, showing that the relationship between concentration of pollutants and their degree of pollution hazards exhibited an *S*-type

Table 1
The concentration of heavy metals in leachate at Minhang waste treatment plant.

Sampling Location	Month	*Cd* (mg/L)	*Cr* (mg/L)	*Pb* (mg/L)	*Hg* (μg/L)	*As* (μg/L)
Minhang	March	0.012	0.824	0.247	0.278	2.500
waste	May	0.076	0.468	0.119	14.900	16.100
treatment	July	0.025	0.084	0.224	4.180	0.900
plant	October	0.213	0.092	0.058	4.650	7.600
	Average	0.082	0.367	0.162	6.000	3.700

function characteristic (James and Lee, 1971). That is, initially the degree of pollution hazards caused by low-dose pollutants was not obvious, then the degree of pollution hazards increased quickly along with the continuing increase of pollution dose, and when the pollution dose increased beyond a critical point, the growth of pollution hazards tapered off. A logistic function model was fitted to describe the above phenomenon. Many scholars have followed their work and applied this method to evaluate the degree of pollution hazards caused by pollutants and to estimate the environmental costs of water pollution (Miural, 1990; Ofiara, 2001; Xu and Liu, 2013). In the same way, food waste composting can also produce a large amount of leachate during the treatment process, given that the wastewater contains a host of different types of heavy metals. The wastewater made up of leachate pollutants in a sewage system also exhibits an *S*-type pattern of pollution hazards as shown in Fig. 1. Hence this study used the same method to calculate the pollution hazards rate of heavy metals and to estimate the heavy metals' environmental costs in leachate during food waste composting.

2.4.1. Single pollution hazards rate model

This study defines *n* kinds of heavy metals in leachate during food waste composting, and uses a R_f variable to denote the pollution hazards rate caused by the *f*-type heavy metal. The value of R_f can be applied to establish the differential equation Eq. (1) relating the concentration of heavy metals to the value of environmental costs (Miural, 1990).

$$\frac{dS}{dC_f} = B_f \frac{S}{K}(K - S) \quad (1)$$

where C_f is the mass concentration of the *f*-type heavy metal in leachate (mg/kg); *S* is the environmental costs caused by heavy metals when the mass concentration of heavy metals is C_f ($\times 10^4$ yuan/year); B_f is the proportionality coefficient; *K* is the economic value of water resources ($\times 10^4$ yuan). The integral calculation to solve Eq. (1) enables attaining Eq. (2).

$$S = \frac{K}{1 + A_f exp(-B_f C_f)} \quad (2)$$

where A_f is the constant term obtained in the process of solving the equation, and the other variables already defined in the above.

Eq. (2) essentially conforms to the representation of a Logistic equation, which is commonly used in econometric modeling (Menon and Bhandarkar, 2004). Simplifying the model through standardizing *K*, we can obtain Eq. (3)

$$R_f = \frac{1}{1 + A_f exp(-B_f C_f)} \quad (3)$$

where R_f is the single pollution hazards rate (%) associated with the specific *f*-type heavy metal.

Based on Eqs. (2) and (3) we can estimate the specific *f*-type heavy metal environmental cost as Eq. (4):

$$S = KR_f \quad (4)$$

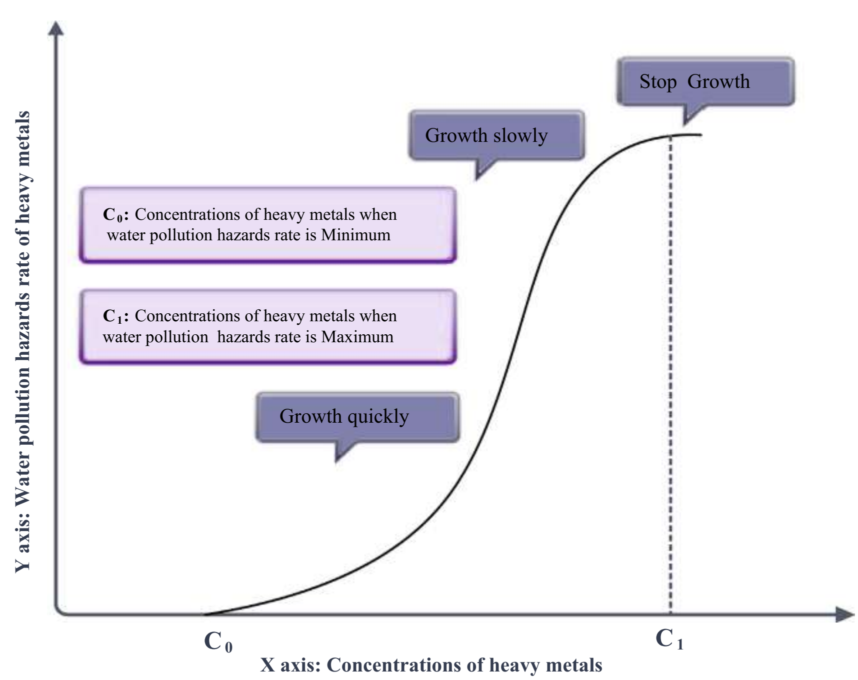

Fig. 1. The growth pattern of water pollution hazards rate with increasing concentration of heavy metals.

2.4.2. The determination of parameters A_f and B_f

As mentioned in the above, A_f ($A_f > 0$) and B_f in Eqs. (2) and (3) are constant terms obtained from solving Eq. (1), and are related to the pollution characteristics of heavy metals. It is thus generally necessary to conduct the pollution toxicology experiments or to investigate the contaminated water environment. This paper employs the *A*-level standard of the limitation on emission of the first-class pollutants in Shanghai integrated wastewater discharge standard, (DB 31/199-2009), as the background concentration, and uses the value of the utmost extent allowable emission of the first-class pollutants as the concentration in the critical pollution state (GB 8978-1996) (SEPB, 2009; SEPA, 1996). In other words, this study uses the integrated wastewater discharge standard in Shanghai (IWDSS) as the background concentration and employs the integrated wastewater discharge standard (IWDSC) as the concentration in the critical pollution state (SEPB, 2009; SEPA, 1996). It is assumed that the comprehensive loss rate of heavy metals in the background concentration state and the critical pollution state is 1% and 99%, respectively. The specific process of this approach is as follows.

This study defines a C_{pf} variable as the background concentration of the *f*-type heavy metal in leachate during food waste composting, and denotes the corresponding single pollution hazards rate as R_{pf}. This study sets a C_{qf} variable as the critical concentration when serious pollution occurs and defines R_{qf} as the corresponding single pollution hazards rate. A binary system of equations is shown in Eq. (5) when the variables C_{pf}, R_{pf}, C_{qf} and R_{qf} are computed using Eq. (3).

$$\begin{cases} R_{pf} = \frac{1}{1+A_f exp\left(-B_f C_{pf}\right)} \\ R_{qf} = \frac{1}{1+A_f exp\left(-B_f C_{qf}\right)} \end{cases} \tag{5}$$

To facilitate calculation, H_f is introduced to express and presented in Eq. (6).

$$H_f = ln\frac{R_{qf}(1-R_{pf})}{R_{pf}(1-R_{qf})} \tag{6}$$

A_f and B_f can then be solved according to Eqs. (5) and (6).

$$\begin{aligned} & A_f = \left[(1-R_{pf})/R_{pf}\right]exp\left[H_f C_{pf}/(C_{qf}-C_{pf})\right] \\ & \text{or } A_f = \left[(1-R_{qf})/R_{qf}\right]exp\left[H_f C_{qf}/(C_{qf}-C_{pf})\right] \\ & B_f = H_f/(C_{qf}-C_{pf}) \end{aligned} \tag{7}$$

2.4.3. Comprehensive pollution hazards rate model

This study assumes that there are *n* kinds of heavy metals in leachate during food waste composting that contaminate water resources, and measures the extent of pollution hazards with a comprehensive pollution hazards rate, denoted by *R*. Assuming no significant synergistic and antagonistic effects of various heavy metals, and based on the basic results of set theory and probability theory, we can compute the comprehensive pollution hazards rate using Eq. (8) (Huang and Wang, 2003):

$$R = 1 - \prod_{f=1}^{n}(1-R_f) \tag{8}$$

where *R* is the comprehensive pollution hazards rate (%); *n* is the types of heavy metals in leachate and R_f is the pollution hazards rate caused by the specific *f*-type heavy metal.

2.4.4. The reliability tests

Many studies have demonstrated that the background concentration and critical concentration have a greater effect on the calculated results when using a logistic function method (Xu and Liu, 2013; Hu, 2015). This study employs *I* standard of the basic project standard limits in the surface water quality, known in the document as "the environmental quality standard of surface water" EQSSW (GB 3838-2002), as the background concentration. This study uses the value of the utmost allowable emission extent of the first-class pollutants, named in the document as "the integrated wastewater discharge standard" (GB 8978-1996), as the concentration in the critical pollution state (SEPA, 2002, 1996). The concentration of heavy metals in different standard can be seen in Table 2. It appears that the concentrations of various heavy metals in IWDSC are ten times of those heavy metals concentrations in IWDSS, while the concentrations of various heavy metals in IWDSC are much higher than the concentrations of heavy metals in EQSSW. These differences in the concentrations of heavy metals offer the possibility to conduct reliability testing later.

It is assumed that the comprehensive pollution hazards rates of heavy metals in the background concentration state and the critical pollution state are 1% and 99%, respectively. When the study quotes the data from the environmental quality standards of surface water (EQSSW), the concentration of *Cr* is three times that of hexavalent chromium as the study assumes. In this case, the comprehensive pollution hazards rate is obtained with EQSSW employed as the background concentration. In this case the computational process to obtain the comprehensive pollution hazards rate is the same process when IWDSS was used as background concentration in Section 2.4.2. By comparing the differences of these two comprehensive pollution loss rates, the reliability of the study can be detected and established.

2.4.5. Classification the degree of water pollution hazards

The water quality situation corresponding to the inflection points (in Fig. 1) directly reflects the sensitivity degree of mutual influence between water environment and human activities. The three inflection points corresponding to the pollution hazards rate and the critical concentration of water pollution are selected as the basis for classifying the degree of water pollution hazards. For easy use in assessing water pollution, we make 0.01, $(3-\sqrt{3})/6$, 0.5, $(3+\sqrt{3})/6$ approximately equal to 1%, 20%, 50%, 80%, respectively. These integer percentages are employed as the classification criteria for measuring the extent of water pollution hazards. According to Li et al. (2009), the degree of hazards degree is obtained, as shown in Table 3.

2.4.6. The estimation of heavy metals' environmental costs

The value of environmental costs caused by *n* types of heavy metals in leachate during food waste composting is calculated using Eq. (9) (Hu, 2015; Xu and Liu, 2013):

$$S = R * Q * P_{water} \tag{9}$$

where *S* is the value of environmental costs caused by heavy metals ($\times 10^4$ yuan/year), as mentioned earlier; *R* is the aforementioned comprehensive pollution hazards rate (%); *Q* is the amount of leachate ($\times 10^4$ tonne/year) and P_{water} is the unit price of industrial water (yuan/tonne).

3. Results and discussion

3.1. Quantitative evaluation of heavy metals' pollution hazards in leachate during food waste composting

This paper computes single pollution hazards rate and comprehensive pollution hazards rate through the following process. The study firstly uses the integrated wastewater discharge standard in Shanghai (IWDSS) as the background concentration and employs the integrated wastewater discharge standard (IWDSC) as the

Table 2
The concentration of heavy metals in different standard (China Standard).

Heavy metals Concentrations	*Cd* (mg/L)	*Cr* (mg/L)	*Pb* (mg/L)	*Hg* (μg/L)	*As* (μg/L)
IWDSS	0.010	0.150	0.100	5.000	50.000
IWDSC	0.100	1.500	1.000	50.000	500.000
EQSSW	0.001	0.030	0.010	0.050	50.000

IWDSS-Integrated wastewater discharge standard in Shanghai.
IWDSC-Integrated wastewater discharge standard in China.
EQSSW-Environmental quality standard of surface water.

Table 3
The classification of the degree of hazards.

The hazards rate of pollution/%	[0,1]	(1,20]	(20,50]	(50,80]	(80,100]
The degree of hazards	No hazards	Minor hazards	Medium hazards	Severe hazards	Loss of function

concentration in the critical pollution state (SEPB, 2009; SEPA, 1996). The parameters A_f and B_f are further determined by combining Eqs. (6) and (7) (Table 4). Finally, this study uses Eq. (3) to obtain the single pollution hazards rate (Fig. 2) and employs Eq. (8) to arrive at the comprehensive pollution hazards (Fig. 3).

When the data from IWDSS is used as the background concentration, the comprehensive pollution hazards rate is 94.48% (see Fig. 3). When the data from EQSSW (see Table 2) is employed as the background concentration, the comprehensive pollution hazards rate, computed with the same process to get the result in Fig. 3, becomes 95.63%. The resulting difference in computing the comprehensive pollution hazards rates between the two cases is a mere 1.15%. This suggests that using different background concentration standards makes little differences in evaluating the comprehensive pollution hazards in leachate with heavy metals during food waste composting. Thus, a logistic function method in this application is relatively reliable (Xu and Liu, 2013; Hu, 2015).

From Table 1 and Fig. 2, we can see that in March, *Cr* is the type of heavy metal showing the highest concentration of 0.824 mg/L and the pollution hazards rate of 49.83%, while the pollution hazards rate of *Cd* is the highest in October, 99.99%, with its concentration being 0.213 mg/L. These findings agree with most of other studies that also show that various types of heavy metals generally have different toxicity (Singh et al., 2015; Adelopo et al., 2018; Huang et al., 2011). For example, Singh et al. (2015), adopting the potential ecological risk index approach, also proved that the eco-toxicity of *Cd* is greater than *Cr*. Due to the different toxicity of heavy metals, it should be cautioned not to simply compare the extent of concentration of different heavy metals to determine the need for technical treatment (Singh and Lee, 2015; Shi et al., 2013). It might be advisable to use the pollution hazards rate of heavy metals to decide which heavy metal should be selected for treatment, because of the measure's relative reliability in assessing the severity of water pollution (Miural, 1990; Ofiara, 2001; Xu and Liu, 2013).

Fig. 2 indicates that the average pollution hazards rate of heavy metals displays the following sequence of severity: *Cd* > *Cr* > *Pb* > *Hg* > *As*, and the comprehensive hazards rate of heavy metals is as high as 94.48% (Fig. 3). According to the classifying standard of hazards, this degree of water pollution hazards caused by heavy metals together falls into the classification of "loss of function", the highest degree of hazards (see Table 3). Fig. 2 shows that the pollution hazards rate of *Cd* is the highest, 94.03%. By the classification standard of hazards degree in Table 3, the water pollution hazards caused by *Cd* belong to loss of function. The pollution hazards rates of *Cr*, *Pb* and *Hg* were 4.24%, 1.87% and 1.22% respectively (see Fig. 2), falling in the range of minor hazards (see Table 3). The pollution hazards rate of *As* is 0.39%, which is classified as no hazards. Thus, our study has established that the pollution hazards of heavy metals mainly come from *Cd* and *Cr*. In contrast, scholars have found that in Malaysia the pollution hazards of heavy metals in food waste composting principally stem from *Cu, Pb, Ni*, and the pollution hazards of *Cd* are relatively low (Kadir et al., 2017). The different findings between these two studies could be because food wastes are mixed with materials that contain different heavy metals and also because administrators in both countries adopt different ways to manage the sorting work of mixed materials. (Hamid et al., 2012; Thi, et al., 2015; Bernstad and La, 2011). *Cd* is primarily contained in waste glass, electrical appliances, plastics, rust-proof metals, semiconductors, pigments, etc. (Manfredi et al., 2010), while *Cr* primarily exists in plastics, glass, newspapers, film, textiles, weeds and so on (Huerta-Pujol et al., 2010). In addition, the pollution hazards rate of *Cd* and *Cr* in March, July, October does not synchronously change (see Fig. 2). Therefore, in Shanghai China, the pollution hazards contributors of heavy metals including *Cd* and *Cr* may be from the plastics that are mixed into the food waste in May.

The pollution hazards severity of heavy metals in March is revealed in the order of *Cr* > *Pb* > *Cd* > *Hg* = *As*, with the pollution hazards rate being 49.83%, 4.34%, 1.22%, 0.38%, and 0.38% respectively (see Fig. 2). According to Table 3, the degree of water pollution caused by *Cr*, *Pb*, *Cd*, *Hg*, *As* pertains to medium hazards, minor hazards, minor hazards, no hazards, and no hazards respectively. Thus, the pollution hazards rate of *Cr* and *Pb* is both relatively high in March. It is known that waste paper mainly contains heavy metals such as *Cr* and *Pb* (SIDRE, 2014; Surtiningsih, 2014; Hamm et al., 1986). Thus, the fact that *Cr* and *Pb* simultaneously showing high pollution hazards rate is probably because food waste was mixed with waste paper.

Table 4
The value of A_f and B_f obtained by combining Eqs. (6) and (7).

	Cd	*Cr*	*Pb*	*Hg*	*As*
A_f	274.85882	274.85882	274.85882	274.85882	274.85882
B_f	102.11377	6.80758	10.21138	204.22755	20.42275

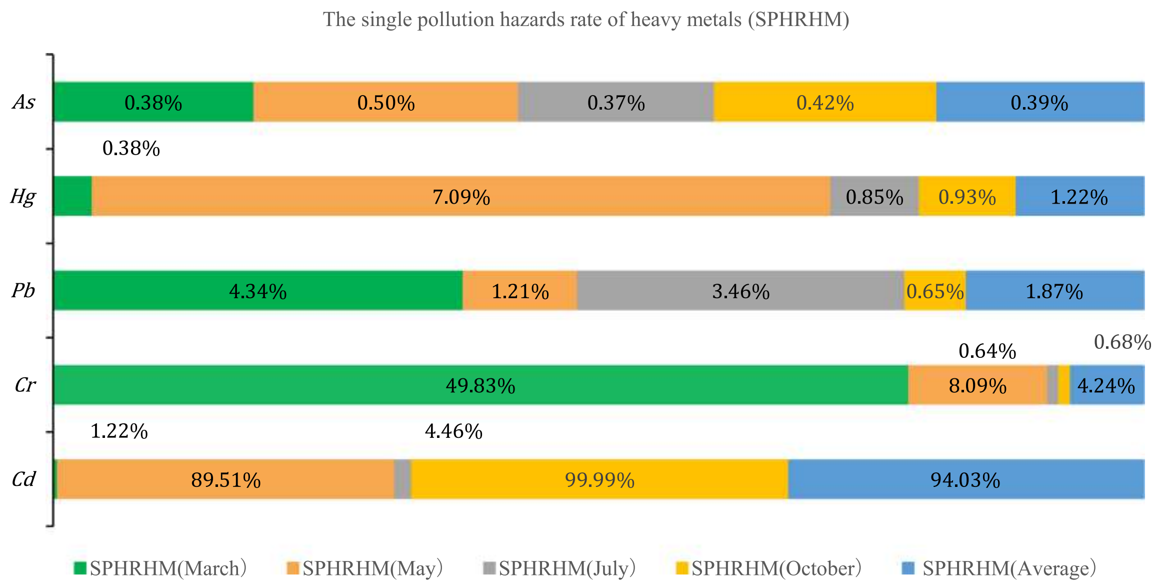

Fig. 2. The single pollution hazards rate of each heavy metal (*Cd, Cr, Hg, Pb* and *As*) in March, May, July, October.

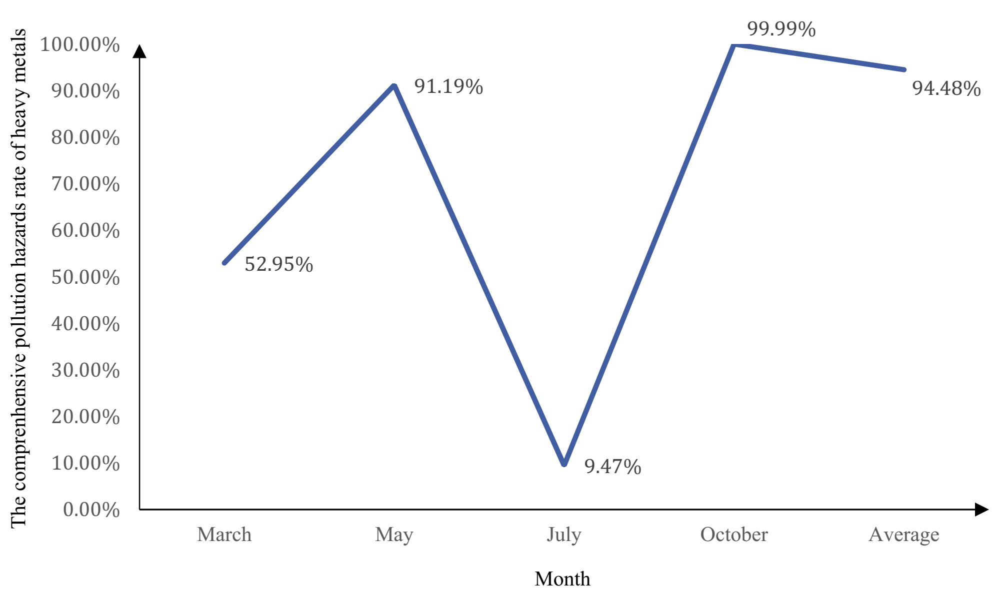

Fig. 3. The variation of comprehensive pollution hazards rate of heavy metals (*Cd, Cr, Hg, Pb* and *As*) in March, May, July, October.

The severity ranking of pollution hazards in heavy metals in July is presented as *Cd* > *Pb* > *Hg* > *Cr* > *As*, with the pollution hazards rate being 4.46%, 3.46%, 0.85%, 0.64%, and 0.37% respectively (see Fig. 2). According to Table 3, the degree of water pollution caused by *Cd, Pb, Hg, Cr, As* belongs respectively to minor hazards, minor hazards, no hazards, no hazards, and no hazards. Thus, only *Cd* and *Pb* posed minor hazards in July. This could be because of the food mix in heavy metals which is associated with the seasonal diet such as charcoal kabobs and tinfoil mushrooms, respectively (Iqbal and Kim, 2016; Sharp and Turner, 2013; Zhang et al., 2008). The concentration of *Cr* not at the elevated level to pose pollution hazards in July perhaps because the food waste at this time is not heavily mixed with plastics, glass, waste paper, which tend to increase the concentration level (SIDRE, 2014; Surtiningsih, 2014). On the other hand, the typical summer diet of people in Shanghai is to eat barbecue food, which may contain a small amount of *Pb* (Sharp and Turner, 2013).

Fig. 2 also indicates that the severity of pollution hazards of heavy metals in October displays the ranking of *Cd* > *Hg* > *Cr* > *Pb* > *As*, with the pollution hazards rate being, respectively, 99.99%, 0.93%, 0.68%, 0.65%, and 0.42%. Thus, only the heavy metal *Cd* presents severe pollution hazards, while other heavy metals are in the no hazards range (see Table 3). *Cd* is known to be present in trust-proof metals (SIDRE, 2014). In this case, materials such as plastics, glasses, and waste papers are not at fault, because from the foregoing analysis, excessive amounts of these substances can lead to increased levels of pollution from other heavy metals, especially *Cr* and *Pb*, which all not showing threats at this time (Manfredi et al., 2010; Surtiningsih, 2014; Hamm et al., 1986). Therefore, it is speculated that the rust-proof metals are mixed with the food waste in October to cause significant pollution hazards.

The above discussions indicate that a mixture of various materials containing heavy metals pose pollution hazards before food waste is formally processed by composting treatment. And these materials not only produce leachate that exceeds the discharge standards of heavy metals, but also affect the quality of composting products (Veeken and Hamelers, 2002). More investment in the sorting technology and strengthening the supervision and management of sorting system are possible solutions to alleviate the problematic amount of heavy metals in leachate during food waste composting (Thi et al., 2015; Zhang et al., 2008). In particular, it is essential to improve the sorting management of *Cd*-containing materials because *Cd* appears to be the main contributor to the high pollution hazards rate in this case.

3.2. Estimation of heavy metals' environmental costs in leachate during food waste composting

Table 1 shows that the concentration of *Cd* and *Cr* fluctuates greatly between months. As can be seen from Figs. 2 and 3, *Cd* exerts large effect on the comprehensive pollution hazards rate. Hence the effect of *Cd* fluctuation on the environmental costs of water pollution needs to be addressed. Fig. 2 shows that the concentration of *Cd* in October is about 18 times of that in March. It is suspected that for some reason the sorting system in October may have gone wrong resulting in substantial deviation October's concentration of *Cd* from other months, including March, May, July. We then take the average of the *Cd* concentration in March, May and July as the new mean of *Cd* concentration under the normal sorting system to calculate the comprehensive pollution hazards rate. The resulting new mean concentration of *Cd* is 0.0376 mg/L, similar to 0.038 mg/L, and the resulting comprehensive pollution hazards rate is 21.39%. This new comprehensive pollution hazards rate under the normal sorting condition is used to calculate the environmental costs caused by heavy metals. Assuming that the density of the leachate is 1 g/mL (Hu, 2015), the estimation results of environmental costs are calculated using Eq. (9) and presented in Table 5 (under actual classification including October *Cd* concentration) and Table 6 (assuming normal sorting system excluding the outlier *Cd* concentration in October).

When the comprehensive pollution hazards rate is 94.48% (see Table 5) and 21.39% (see Table 6), the environmental costs caused by heavy metals in leachate during food waste composting respectively amount to 159.4 thousand yuan (US$24328) and 36.1 thousand yuan (US$5510) in 2014. It suggests that the environmental costs generated by the actual classification is 5 times the environmental costs under the good sorting condition. This difference in environmental costs mainly derives from the changes in *Cd* concentration due to its high pollution hazards (Manfredi et al., 2010). From an environmental cost perspective, it thus underscores the importance of improving the management of sorting system in the process of the front-end disposal (prior to disposal).

This paper provides a concrete estimate of the environmental costs caused by heavy metals in leachate during food waste composting, which are specifically 3.42 yuan/tonne (or about US$0.52 per tonne). This makes up the gap in the literature wherein researchers have focused more on the environmental costs caused by carbon or nutrient substances (Maalouf and El-Fadel, 2017; Chen, 2016; Xu and Liu, 2013). Additionally, it should be noted that the environmental costs (3.42 yuan/tonne) of heavy metals' pollution estimated here may be lower than the actual values. This is because the market price of water is used in our estimation instead of the value of water as a natural resource, and it is likely that the market price of water understates the total value of water resources (Saliba et al., 1987; He et al., 2007; Hu, 2015).

When it comes to setting the food waste charges, it should be necessary to incorporate the external cost arising during the process of food waste composting. Many studies have confirmed that increasing the charging fees can reduce waste emissions under the polluter-pays principle (Folz and Giles, 2002; Skumatz and Freeman, 2006). Hence, we would advocate that the 3.42 yuan/tonne environmental costs should be charged as a part of the food waste treatment fee under the polluter-pays principle. Such environmental costs surcharges are meaningful and relevant, considering that they are equivalent to 2.97% of Shanghai's food waste treatment charges (SMDRC, 2014). Furthermore, because heavy metals can cause severe physical hazards even at low concentrations (Soobhany et al., 2015; Guertin, 2004; Lopes et al., 2011), further study should not only consider the environmental costs when calculating the external costs of water pollution caused by heavy metals, but also should take the social costs of the physical hazards caused by heavy metals into account.

Regardless of whether the comprehensive pollution hazards rate is set at 21.39% or 94.48%, this study reports that the environmental costs of heavy metals are rising over years (see Table 5, Table 6). This is because the continuing urbanization and expansion of Shanghai, and the increasing migration of rural population into Shanghai, are bound to increase the quantities of food waste significantly (Ying et al. (2015)). In turn, it will also the environmental costs of heavy metals. With the growing amount of food waste expected to be generated, it becomes even more important to reduce heavy metals in leachate (Veeken and Hamelers, 2002).

3.3. Comparison with previous studies and discussion of possible limitations

This paper used a logistic function approach to evaluate pollution hazards rate and environment coasts in water environment. Some researchers (Miural, 1990; Ofiara, 2001; Huang and Wang, 2003; Xu and Liu, 2013; Hu, 2015) using the same approach have acknowledged limitations of this method. For one, the accuracy about evaluation results of heavy metals pollution hazards depends on the reliability of parameters (A_f,B_f), which in turn depends on the reliability of the water environmental quality standard and discharge standard set by the government. Table 7 shows

Table 5
The environment costs caused by heavy metals in leachate during food waste composting when CPHRHM[a] is 94.48%.

Year	CPHRHM[a]	Water unit price (yuan[b]/tonne)	Per tonne environmental costs (yuan[b]/tonne)	Quantity of leachate ($\times10^4$ tonne/year)	Annual environmental costs ($\times10^4$ yuan[b]/year)
2014	94.48%	3.62	3.42	4.66	15.94
2015	94.48%	5.00	4.72	4.76	22.49
2016	94.48%	5.00	4.72	4.87	23.00
2017	94.48%	5.00	4.72	4.99	23.57
2018	94.48%	5.00	4.72	5.12	24.19
2019	94.48%	5.00	4.72	5.23	24.71
2020	94.48%	5.00	4.72	5.42	25.60

[a] Comprehensive pollution hazards rate of heavy metals.
[b] 1USD $= 6.5521 RMB yuan in 2018.

Table 6
The environment costs caused by heavy metals in leachate during food waste composting when CPHRHM[a] is 21.39%.

Year	CPHRHM[a]	Water unit price (yuan[b]/tonne)	Per tonne environmental costs (yuan[b]/tonne)	Quantity of leachate ($\times 10^4$ tonne/year)	Annual environmental costs ($\times 10^4$ yuan[b]/year)
2014	21.39%	3.62	0.77	4.66	3.61
2015	21.39%	5.00	1.07	4.76	5.09
2016	21.39%	5.00	1.07	4.87	5.21
2017	21.39%	5.00	1.07	4.99	5.33
2018	21.39%	5.00	1.07	5.12	5.47
2019	21.39%	5.00	1.07	5.23	5.60
2020	21.39%	5.00	1.07	5.42	5.80

[a] Comprehensive pollution hazards rate of heavy metals.
[b] 1USD $= 6.5521 RMB yuan in 2018.

Table 7
The concentration of heavy metals in different standard (European Union Standard).

Heavy metals Concentrations	*Cd* (mg/L)	*Cr* (mg/L)	*Pb* (mg/L)	*Hg* (μg/L)	*As* (μg/L)
IWDSEU	0.015	0.300	0.100	3.000	100.000
EQSWEU	0.005	0.050	0.010	1.000	10.000

IWDSEU-Integrated wastewater discharge standard in European Union.
EQSWEU-Environmental quality standard of water in European Union.

the environmental quality standard of water in European Union (EQSWEU), which differs with China's (EQSSW) (see Table 3) (Sanchez and Porcher, 2009). For example, the European's concentration standards of *Cd*, *Cr*, *Hg* are higher than China's in EQSSW. The integrated wastewater discharge standard in European Union (IWDSEU) is also different from China's (IWDSC) (see Table 3, Table 7). In addition, the integrated wastewater discharge standard of heavy metals in Japan (*Cd* 0.1 mg/L, *Cr* 0.5 mg/L, *Pb* 0.1 mg/L, *Hg* 5 μg/L, *As* 100 μg/L) is also different with European Union (*Cd* 0.015 mg/L, *Cr* 0.3 mg/L, *Pb* 0.1 mg/L, *Hg* 3 μg/L, *As* 100 μg/L) and China (*Cd* 0.1 mg/L, *Cr* 1.5 mg/L, *Pb* 1 mg/L, *Hg* 50 μg/L, *As* 500 μg/L) (Matsuo et al., 2011). These standards are developed in various countries according to their status of water management. Conceivably the differences in standards will influence the value of A_f and B_f and further affect the environmental costs. Thus, estimation of environmental costs is subject to variations in environmental standards, and this would limit, to some extent, the validity of cross-country comparisons.

Another possible limitation is the source of data, especially the accuracy of heavy metals' concentration (see Table 1). As presented in Section 2.3, our data came from a report (SIDRE, 2014), which investigated the concentration of heavy metals in leachate during food waste composting in March, May, July and October during 2014. The sampling process may affect the accuracy of calculation results to some degree. Typically, a survey like this case needs to engage in multiple random sampling in every month and quarter (Liu et al., 2011; Hu, 2015; Lopes et al., 2011). For example, Liu et al. (2011) chose 99 sampling sites and collected 6–8 samples in each place (sampling site), which would greatly increase the accuracy of the data since the large sample of data can reduce random error. But when facing the reality of experimental conditions (human costs, physical costs and financial costs, particularly the limited funds), many researchers are constrained and unable to afford collecting a large sample (Huang et al., 2011; Azizi et al., 2015; Singh et al., 2015). For instance, Huang et al. (2011) apply two kinds of liquefaction residue samples to do the experiment of measuring heavy metals' pollution hazards. Our study is in line with Singh et al. (2015) in the process of sample selection, and both studies use a quartering method to acquire the sample. Hence, it is expected that the results of this study are reasonably reliable.

4. Conclusions

This paper presents a quantitative approach to evaluate heavy metals' pollution hazards in leachate during food waste composting. This approach is associated with the concentration of heavy metals and the heavy metals' discharging standard set by national or local government. The findings indicate that the pollution hazards rate of *Cd* amounts to 94.03%, probably because the *Cd*-containing materials such as plastics are mixed in food waste. The pollution hazards rates of *Cr*, *Pb*, *Hg* and *As* are 4.24%, 1.87%, 1.22% and 0.39% respectively, partly due to the mixing of a small amount of waste paper or the rust-proof metals and the summer diet of eating barbecue food in Shanghai.

Using the calculation results of comprehensive pollution hazards rate, we then estimate the environmental costs. The environmental costs caused by heavy metals in leachate during food waste composting are found to be about US$0.52 per tonne under the condition of comprehensive pollution hazards rate being 94.48%. This magnitude of environmental costs is nontrivial and meaningful, considering that it is equivalent to 2.97% of Shanghai's food waste treatment charges. We advocate that by the polluter-pays principle (Pay-As-You-Throw), the environmental costs caused by heavy metals in leachate as a part of the external cost should be calculated and incorporated in setting waste treatment charges.

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