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Life cycle risk assessment of bottom ash reuse

Hsiu-ching Shih, Hwong-wen Ma*

Graduate Institute of Environmnental Engineering, National Taiwan University, 71, Chou-Shan Road, Taipei 106, Taiwan

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ABSTRACT

The life cycle thinking was integrated with risk assessment to develop the life cycle risk assessment (LCRA) methodology in this study. Because LCRA assessed risks from a life cycle perspective of the concerned policies, it was helpful to identify important sources, contaminants, receptors and exposure pathways along the life cycle of reuse activities. The case study showed that different reuse scenarios resulted in risk shift between different life stages and receptors, and using duration of pavement was an essential factor for risk management. When ash reuse strategies were made based on a focus on the stage of reuse, the rank of strategies were shown to be different from the one based on the total population risks over the entire life cycle. This demonstrated the importance of decision criteria used in selecting reuse strategies. The results also showed that when bottom ash was reused, the health risk was shifted to the laborers; the individual risks of laborers were higher than residents through exposure to Cr and Cd via inhalation and dermal contact. Although the population risk at the treatment stage was the highest, the smaller size of exposed population would make it quite effective to reduce the risk of the laborers.

1. Introduction

As the waste incineration rate has risen from 3.03% in 1993 to 52.20% in 2009 [1], frequent burning of waste has led to an increased amount of fly ash and bottom ash, which used to be landfilled [2]. However, because of limited landfill sites on one hand and the presence of Si, Ca, Al, and Fe in bottom ash on the other hand, bottom ash is now increasingly used for construction as opposed to final landfill disposal [3,4]. A practice now commonly seen in Denmark, Belgium, and the Netherlands is to use bottom ash to repair roads and produce asphalt concrete, permeable pavement, and bricks. Above all, the reuse of bottom ash in road paving has reached 100% in the Netherlands [5,6]. Although the reuse of bottom ash is appealing, the issue of potential environmental impact associated with the reuse has emerged [7].

Bottom ash has been shown to have similar characteristics useful for engineering applications as natural aggregate. Road paving with bottom ash seems to be feasible [8], but leaching from reused bottom ash was still the main release mechanism while bottom ash was used in road paving [9,10]. Because of the leaching potential of reused bottom ash, risk assessment (RA) has been conducted on bottom ash reuse. In the U.S.A., the assessment of bottom ash reuse in asphalt and cement, structure protection material, and road paving and covering of landfill has shown that the individually estimated risks of these applications were slightly greater than 1.0E−06 [11]. Another example is that the human health risk of road repairing with bottom ash has been estimated to be minimal in a typical UK situation [5]. RA was used in these above studies to focus on the individual source, such as landfill, road paving and road repairing individually, but the link between one source and another has not been considered. When an activity such as bottom ash reuse involves a sequence of potential risk sources, separate assessments of the risk sources are not sufficient to provide the whole picture of the impact of the activity and a due consideration of risk shifts between sources. For bottom ash reuse, in order to avoid risk shifts among sources, the risk assessment has to cover the whole process, including treatment, reuse, even and post reuse. Therefore the whole life cycle of bottom ash reuse should be considered and linked with RA.

Some studies have linked risk assessment and life cycle assessment to evaluate the comparative impact from a life cycle process, which is a risk-based life cycle assessment (LCA). Risk-based LCA integrates RA into LCA to improve the accuracy and detail of LCA [12,13], by evaluating the emission, distribution and accumulation of concerned contaminants [14], which then transforms into intake fraction. Intake fraction has been defined as the intake dose per unit emission rate. The intake dose can be calculated by multiplying the concentration of a contaminant, the exposure rate and the number of exposed people [15]. Although intake fraction has incorporated fate and exposure factors in risk-based LCA, it is quite simplified in that full environmental transport modeling is not employed, an example being that the effects of meteorology and elevation are not taken into account, and the exposure factor does not differentiate categories of receptors. The population intake fraction of potential human exposure to a toxic pollutant was calculated with CalTOX and the uniform system adapted for LCA evaluation of substances

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* Corresponding author. Tel.: +886 2 23630406; fax: +886 2 23928830.
E-mail address: hwma@ntu.edu.tw (H.-w. Ma).

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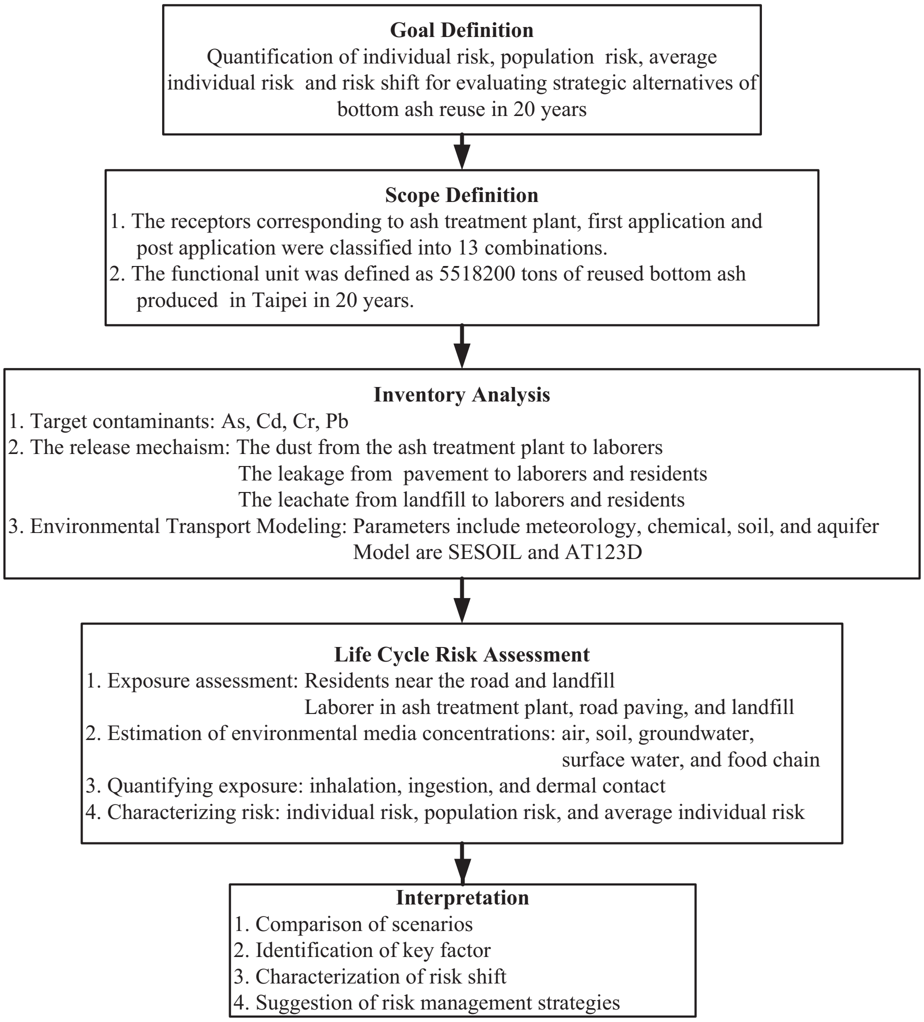

Fig. 1. Methodology of LCRA in this study.

[16]. The method has been used to characterize comparative environmental impacts such as the harm to drinking water from the use of virgin aggregate and recycled materials in roadway construction [17].

Because of the weakness of the risk-based LCA in taking into account temporal and spatial heterogeneity and distinguishing between various receptors, this study approaches the linage of risk and life cycle consideration from a different angle. In order to maintain the link between source and receptor through RA, and consider a life cycle in bottom ash reuse, the method in this study focuses on integrating life cycle thinking into RA, which can be termed life cycle risk assessment (LCRA). In this study, RA is performed at all life stages from the treatment process, application process, to disposal. The purpose of this study is to integrate life-cycle thinking into RA and avoid the risk shift while bottom ash reuse is conducted. As a case study, different scenarios of bottom ash reuse in road paving are assessed using the LCRA. Section 2 presents the methodology, followed by the results and discussion of the method and the case study in Section 3. Finally Section 4 summarizes the merits and limitations of the method.

2. Methodology

The methodology of LCRA in this study as shown in Fig. 1 followed the LCA paradigm detailed below [18].

2.1. Goal definition

The goal of assessment for the case study was defined as comparing strategic alternatives of bottom ash reuse in road paving. Strategic alternatives considered mainly the usage duration of pavement because the usage duration of pavement has been identified as an important factor to reduce the leaching of chemicals [19]. Four strategic alternatives are constructed by assumptions of pavement duration and the destination of bottom ash in a specified timeframe. In Taiwan, for the roads with frequent need of electrical cables and water pipelines maintenances, the excavation of pavements happens every 1–3 years; for the roads with less need of maintenance, the pavement usage duration has reached 18.5-year [20]. Therefore 2-year usage duration represented the high frequency of road maintenance, whereas 20-year one represented the upper bound of time span before road maintenance activity took place.

LCRA was used to quantify the total risk and the risk shift associated with bottom ash reuse under four strategic alternatives in 20 years. The four scenarios were as follows. Scenario A: bottom ash was used in road paving; it was excavated and re-paved on the same road every 2 years for road maintenance. Scenario B: bottom ash was used in road paving, excavated and transported to a landfill after 2 years. Scenario C: bottom ash was used in road paving without excavation during the investigation period. Scenario D: bottom ash was not reused but was disposed in landfill without

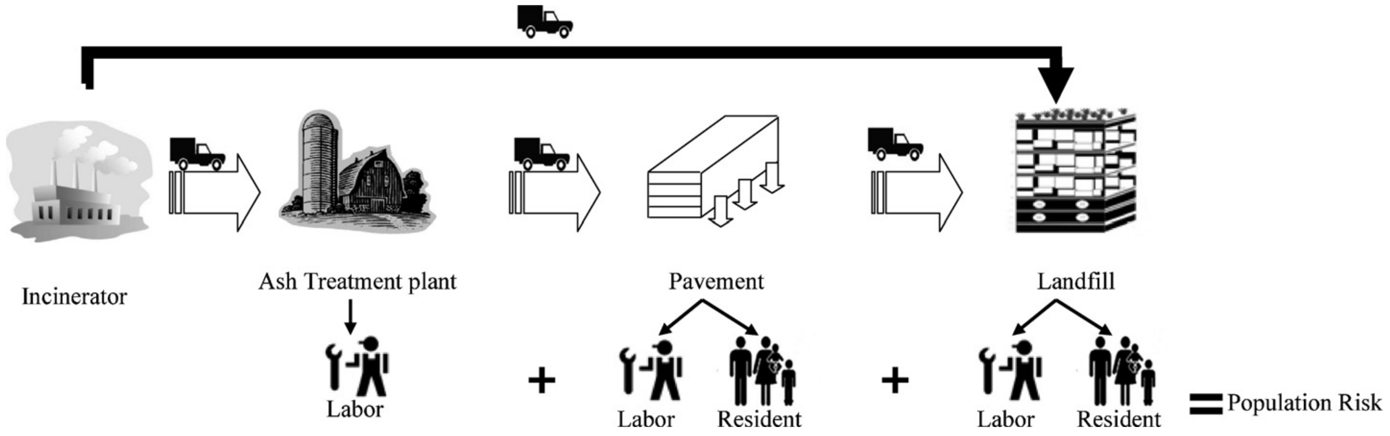

Fig. 2. The sources and receptors over the life cycle of bottom ash reuse considered in this study.

pre-stabilization. The structure of road from top to bottom consisted of four layers based on engineering practice: the top layer was 5 cm thick and composed of 20% bottom ash, the second layer was 5 cm thick and composed of 30% bottom ash, the third layer was 15 cm thick and composed of 20% bottom ash, and the bottom layer was 25 cm thick and composed of 80% bottom ash [21].

2.2. Scope definition

As shown in Fig. 2, the processes of LCRA considered in this study included ash treatment plant, first application, and then post application; the latter two processes included two sources-road paving and landfill. The concerned contaminants were those significantly released through dust from the storage and treatment areas in an ash treatment plant, leakage from the pavement downwards through soil to groundwater, and the leachate from the landfill that was collected and drained to surface-water. Laborers and residents were the concerned receptors; further, residents were classified into ones in working duration and in using duration. There were 13 combinations of receptors and sources, such as laborers in storage of bottom ash, residents in first application in working duration, residents near landfill and so on (as detailed in Table 1). The laborers or residents in the ash treatment plant, road paving and landfill were exposed to the contaminants in bottom ash through inhalation, dermal contact, soil ingestion, and ingestion of water and food contaminated by irrigation using groundwater or surface water.

The functional unit was used as a basis of comparison between alternatives. The functional unit was defined as the 5,518,200 t of reused bottom ash, the quantity produced in Taipei in 20 years [21]. The exposure characteristics of the receptors, including exposure frequency, exposure duration, and the size of population affected, under the four scenarios are listed in Table 1.

2.3. Inventory analysis

The major metals that exist in the bottom ash, including As, Cd, Cr, Cu, Pb and Zn, are the primary concern of reuse of bottom ash. Based on TCLP and toxicity, As, Cd, Cr and Pb were chosen as target compounds [22]. As and Cr are known human carcinogens, and Cd and Pb are identified as probable human carcinogen. No formal carcinogenic and noncarcinogenic data have been developed from toxicity studies of Cu [23,24]. Although Zn has noncarcinogenic effects, it is not considered presently since it is not regulated in the TCLP criteria in Taiwan. In an ash treatment plant, the laborers were exposed to the bottom ash directly through inhalation, dermal contact and soil ingestion. To estimate inhalation exposure to the laborers in the ash treatment plant, the dust of the contaminants resulting from three sections – the storage of bottom ash, the treatment process, and the storage of treated ash, were sampled individually (Table 2).

In addition to the air sampling in the ash treatment plant, the concentrations of the contaminants, As, Cd, Cr, and Pb, were determined to have average values of 236.4, 301.3, 599.7, and 9010.5 mg/kg, respectively [21]. These concentrations were applied in the leakage simulation from the pavement to estimate the contaminant concentrations in groundwater and subsequent exposure media in the food chain resulting from irrigation using the groundwater. Leaking of contaminants from the pavement into the soil and groundwater is an essential mechanism for leading to risk associated with the application of bottom ash [25]. In order to simulate the leakage from the pavement, SESOIL (Seasonal Soil) and AT123D (Analytical Transient 1-, 2-, and 3-dimensional Simulation of Waste Transport in Aquifer System) were used in this research to model the transport mechanism. This mechanism depends on chemical factor and regional factor to evaluate the contaminant concentrations of leakage. SESOIL is a one-dimensional vertical transport model for the unsaturated soil zone [26]. It is designed to simultaneously model water transport, sediment transport, and contaminant fate. AT123D [26] is based on the advection–dispersion equation, which is used to determine the contaminant distribution in groundwater. The model was developed to estimate concentrations of contaminants transported, dispersed, degraded, and adsorbed in one-dimensional groundwater flow. The results of model can be used to estimate how far a contaminant plume will migrate, and to provide the temporal and spatial profiles of a contaminant in the groundwater for subsequent assessment linking groundwater use with other contact media such as food and drinking water.

Because the leachate from the landfill was collected and did not enter the aquifer, the concentrations of As, Cd, Cr, and Pb of 2.2, 0.5, 15.7, and 71.8 μg/L, respectively, measured in the bottom ash monofills leachate were used to approximate the collected leachate concentrations as there is no bottom ash monofill in Taiwan [27–29]. A contaminant removal efficiency of 90% for a leachate treatment facility was assumed [30–33], and after the process of treatment, the leachate was drained into surface water. The dilution coefficient of surface water was estimated by the water body volume, volumetric flow rate through water body, fraction of total water body concentration of a chemical in the water column, overall total water body dissipation rate constant, and depth of upper benthic sediment layer [34].

2.4. Assessment of life-cycle risk

The simulation of leaching and transportation was followed by multi-pathway exposure modeling that addressed the coupling

Table 1
The exposure characteristics of the receptors.

Category	Parameter[a]	Process												
		Ash treatment plant			First-application[d]					Post-application[e]				
		Laborer in the storage of bottom ash	Laborer in the treatment process	Laborer in the storage of treated ash	Laborer	Resident in working duration	Resident in usage duration	Laborer in the landfill	Resident near landfill	Laborer	Resident in working duration	Resident in usage duration	Laborer in the landfill	Resident near landfill
Scenario A	Exposure frequency[a]	86.67	86.67	86.67	86.67	2	363		–	86.67	2	363		–
	Exposure duration[b]	20	20	20	2	1 (event)	2		–	18	9 (event)	18		–
	Affected population[c]	4	20	2	125	165,131	165,131		–	125	908,221	908,221		–
Scenario B	Exposure frequency	86.67	86.67	86.67	86.67	2	363		–	–	–	–	86.67	365
	Exposure duration	20	20	20	20	1 (event)	2		–	–	–	–	18	18
	Affected population	4	20	2	125	165,131	165,131		–	–	–	–	17	168,689
Scenario C	Exposure frequency	86.67	86.67	86.67	86.67	2	363		–	–	–	–		–
	Exposure duration	20	20	20	20	1 (event)	20		–	–	–	–		–
	Affected population	4	20	2	125	1,651,310	1,651,310		–	–	–	–		–
Scenario D	Exposure frequency	–	–	–	–	–	–	86.67	365	–	–	–		–
	Exposure duration	–	–	–	–	–	–	20	20	–	–	–		–
	Affected population	–	–	–	–	–	–	17	168,689	–	–	–		–

[a] Exposure frequency(days/year (event)): the exposure frequency was based on site-survey, e.g., the laborer worked for 8 h every day, five days every week, and fifty-two weeks every year, so every laborer worked 86.67 days every year. The exposure frequency for residents was scenario-specific, e.g., paving a road took 2 days [38].

[b] Exposure duration (years or events/20 years): the exposure duration was scenario-specific.

[c] Affected population (person): the affected populations of laborers were based on site survey in ash treatment plant and a landfill in Taiwan; and the population of the residents living near the road was calculated by multiplying the pavement area by the population density.

[d] First application: the bottom ash in reused or landfilled after the process of treatment.

[e] Post application: the destiny of the bottom ash after it is paved and excavated.

Table 2
The sampled dust concentrations of contaminants in the air (mg/m^3) in the treated ash plant [14].

Sectors	As	Cd	Cr	Pb
Storage of bottom ash	0.0101	0.0078	0.7069	0.6697
Treatment process	0.0151	0.0179	1.116	1.3025
Storage of treated ash	0.0078	0.0019	0.6512	0.0558

between the environmental media (e.g., groundwater and surface water) and the contact media (e.g., drinking water and food chain) to estimate the intake dose received by receptors through inhalation, dermal contact and ingestion of those contact media [35,36]. The exposure parameters are shown in Table 3. According to the data, dose was calculated as the average daily intake of contaminate k (mg/kg-day) resulting from an environmental medium i (such as air or soil) and an exposure medium j (such as milk or vegetable):

$$\mathrm{ADI}_{ijk} = C_{ij} \times \frac{\mathrm{IU}_j}{\mathrm{BW}} \times \frac{\mathrm{EF} \times \mathrm{ED}}{\mathrm{AT}}$$

where C_{ij} (mg/kg or mg/L) is the concentration of the contaminant k in the exposure medium j affected by environmental medium i; IU_j (kg/day or L/day) is the contact rate of exposure medium j; EF (days/year (event)) and ED (years or events/20 years) are the exposure frequency and exposure duration, respectively; AT (days) is the average lifetime; and BW (kg) is an average body weight for risk receptor. Finally, the carcinogenic risk, applied in risk characterization in this study, was the product of the average daily intake and the cancer slope factor for the relevant toxicant (mg/kg-day)$^{-1}$. The individual risks for the receptors of simultaneous exposures to several chemicals from a variety of sources through more than one exposure pathway can be summed [37].

To characterize the risk of the considered life cycle of ash reuse, all the population risks over all sources across the various life stages (13 combinations) were aggregated. The population risk for each of the 13 combinations of source and receptor was calculated by multiplying the individual risk by the number of people exposed. Further, the average individual risk for each of the four evaluation scenarios was also calculated by dividing the total population risk by the total number people.

2.5. Interpretation

By integrating life cycle thinking into human health risk assessment, the risks associated with various receptors at each life stage can be obtained. The overall information should then be interpreted as a basis of decision making at least in the following aspects. First, the results of scenario comparison were used to rank and choose among the alternatives according to a specified criterion. Second, important stages, receptors, exposure pathways and contaminants as well as the driving management factors were identified to facilitate risk management. Third, information of risk shift between different sources and between different receptors under different scenarios helped balance a narrower view that traditional focused on a particular stage or receptor.

3. Results and discussion

3.1. Identification of key chemicals, exposure pathways, and receptors

The individual risks for the four scenarios are shown and discussed below as categorized by exposure pathways (Table 4) and by contaminants (Table 5). With higher exposure, laborers would experience higher risk than residents when bottom ash is reused on the pavement or kept in a landfill. The risk to the laborers in the ash treatment plant through inhalation expose to Cr was critical, due to high concentration of Cr in the air of the plant. The laborers working at the stages of pavement and landfill experienced the largest risk from Cd via dermal contact. As for the residents, the highest individual risk occurred in road paving due to leakage of Cr to groundwater, and the ingestion of drinking water and food chain contaminated by groundwater use were the main exposure pathways. Owing to the low adsorption ability, Cr is the decisive contaminant in the groundwater, although Pb has the highest amount in the bottom ash. Residents living near the landfill also receive Cr through drinking water and food-chain, because of the high toxicity of Cr that was leached from the landfills and collected and drained into surface water.

3.2. Characterization of risk shifts

Comparing the four scenarios with different using duration of pavement, we can find the risk shifts between different stages. For example, when an upper bound of time span, 20 years, was used (scenario C), the individual risk of residents living near the road was 100 times greater than the residents near the landfill which keeps bottom ash for 20 years (scenario D). However, the individual risk of residents living near landfill is 1000 times greater than the residents near the road when a high frequency of road maintenance (2 years) was used. This indicated that different reuse scenarios would result in risk shift between life stages and receptors, and using duration of pavement would be a factor for risk management.

The population risks (Table 6) were shown to be similar in scenarios A, B and C, and scenario D led to the least risk. This clearly indicated that the ash treatment plant caused the risk substantially greater than the stages of first application and post application. Take scenarios C and D as an example, the population risk of scenario C was almost 800 times more than scenario D. For further analysis, while 100% population risk of scenario D resulted from first-application process, more than 97% of the population risk of scenario C resulted from the ash treatment plant. The risk was shifted in sources from first application to the ash treatment plant. Since the number of receptors at the stage of ash treatment under scenario C was actually much smaller than that at the stage of first application (landfill) under scenario D, the risk shift clearly showed that the shift in source had greater effect than the shift in receptor. However, the risk received by a smaller receptor population is relatively easier to be reduced effectively; for example, the 26 persons in the ash treatment plant could be required to wear respirators and long-sleeved clothing to hinder the exposure pathways, even though the population risk becomes much higher after the risk shift.

3.3. Suggestion of risk management strategies

Usually individual risk of residents is the primary concern of bottom ash reuse and serves as the basis of strategy development. The ranking of management alternatives assessed by individual risks of residents is B, A, D and C. On the other hand, when the population risks over the entire life cycle considered in this study are used as a decision criterion, the ranking becomes D, A, B and C. Different considerations may lead to different choices of policies and management strategies. With assessment results of LCRA, the decision makers can obtain information of important life stages,

Table 3
The exposure parameters.

Parameter	Unit	Process														
		Ash treatment plant			First-application					Post-application				
		Laborer in the storage of bottom ash	Laborer in the treatment process	Laborer in the storage of treated ash	Laborer	Resident in working duration	Resident in usage duration	Laborer in the landfill	Resident near landfill	Laborer	Resident in working duration	Resident in usage duration	Laborer in the landfill	Resident near landfill
Adhesion coefficient of soil to dermal[a]	mg/cm^2-skin	7.00E−02	7.00E−02	7.00E−02	7.00E−02	–	–	7.00E−02	–	7.00E−02	–	–	7.00E−02	–
Frequency of soil contact	events/day	1	1	1	1	–	–	1	–	1.00E+00	–	–	1	–
Contact area of arm[a]	cm^2	3460	3460	3460	3460	–	–	3460	–	3460	–	–	3460	–
Exposure of soil contact	days/year	86.67	86.67	86.67	2	–	–	2	–	2	–	–	2	–
Rate of soil ingestion[a]	g/day	0.10	0.10	0.10	0.10	–	–	0.10	–	0.10	–	–	0.10	–
Rate of drinking water[b]	L/day	–	–	–	–	–	1.43	–	1.43	–	–	1.43	–	1.43
Rate of vegetable ingestion[b]	kg/day	–	–	–	–	–	0.292	–	0.292	–	–	0.292	–	0.292
Rate of crop ingestion[b]	kg/day	–	–	–	–	–	0.255	–	0.255	–	–	0.255	–	0.255
Rate of meat ingestion[b]	kg/day	–	–	–	–	–	0.093	–	0.093	–	–	0.093	–	0.093
Rate of milk ingestion[b]	L/day	–	–	–	–	–	0.06	–	0.06	–	–	0.06	–	0.06
Life time[a]	years	75	75	75	75	75	75	75	75	75	75	75	75	75
Body weight[b]	kg	64.56	64.56	64.56	64.56	64.56	64.56	64.56	64.56	64.56	64.56	64.56	64.56	64.56

[a] [39].
[b] [40].

Table 4
The individual risk categorized by exposure pathways.

Category	Exposure	Process												
		Ash treatment plant			First-application					Post-application				
		Laborer in the storage of bottom ash	Laborer in the treated process	Laborer in the storage of treated ash	Laborer	Resident in working duration	Resident in using duration	Laborer in the landfill	Resident near landfill	Laborer	Resident in working duration	Resident in using duration	Laborer in the landfill	Resident near landfill
Scenario A	Inhalation	3.31E−02	5.28E−02	2.91E−02	3.31E−10	3.43E−15	6.63E−13	–	–	2.98E−09	1.64E−14	5.97E−12	–	–
	Drinking	–	–	–	–	–	–	–	–	–	–	–	–	–
	Dermal	2.47E−04	2.47E−04	2.47E−04	9.27E−06	–	–	–	–	8.34E−05	–	–	–	–
	Soil-ingesting	5.12E−07	5.12E−07	5.12E−07	1.91E−08	–	–	–	–	1.72E−07	–	–	–	–
	Food-chain	–	–	–	–	–	–	–	–	–	–	–	–	–
Scenario B	Inhalation	3.31E−02	5.28E−02	2.91E−02	3.31E−09	3.43E−15	6.63E−13	–	–	–	–	–	2.98E−09	–
	Drinking	–	–	–	–	–	–	–	–	–	–	–	–	6.71E−11
	Dermal	2.47E−04	2.47E−04	2.47E−04	9.27E−05	–	–	–	–	–	–	–	8.34E−05	–
	Soil-ingesting	5.12E−07	5.12E−07	5.12E−07	1.91E−07	–	–	–	–	–	–	–	1.72E−07	–
	Food-chain	–	–	–	–	–	–	–	–	–	–	–	–	9.08E−11
Scenario C	Inhalation	3.31E−02	5.28E−02	2.91E−02	3.31E−09	3.43E−15	6.64E−12	–	–	–	–	–	–	–
	Drinking	–	–	–	–	–	4.61E−09	–	–	–	–	–	–	–
	Dermal	2.47E−04	2.47E−04	2.47E−04	9.27E−05	–	–	–	–	–	–	–	–	–
	Soil-ingesting	5.12E−07	5.12E−07	5.12E−07	1.91E−07	–	–	–	–	–	–	–	–	–
	Food-chain	–	–	–	–	–	6.26E−09	–	–	–	–	–	–	–
Scenario D	Inhalation	–	–	–	–	–	–	3.31E−09	–	–	–	–	–	–
	Drinking	–	–	–	–	–	–	–	7.45E−11	–	–	–	–	–
	Dermal	–	–	–	–	–	–	9.27E−05	–	–	–	–	–	–
	Soil-ingesting	–	–	–	–	–	–	1.91E−07	–	–	–	–	–	–
	Food-chain	–	–	–	–	–	–	–	1.01E−10	–	–	–	–	–

Table 5
The individual risk categorized by contaminants.

Category	Material	Process												
		Ash treatment plant			First-application					Post-application				
		Laborer in the storage of bottom ash	Laborer in the treatment process	Laborer in the storage of treated ash	Laborer	Resident in working duration	Resident in usage duration	Laborer in the landfill	Resident near landfill	Laborer	Resident in working duration	Resident in usage duration	Laborer in the landfill	Resident near landfill
Scenario A	As	2.56E−03	3.82E−03	1.98E−03	6.33E−07	3.99E−16	7.73E−14	–	–	5.70E−06	1.92E−15	6.96E−13	–	–
	Cd	1.04E−03	2.11E−03	4.16E−04	8.07E−06	2.14E−16	4.14E−14	–	–	7.26E−05	1.03E−15	3.73E−13	–	–
	Cr	2.92E−02	4.62E−02	2.69E−02	4.50E−07	2.77E−15	5.36E−13	–	–	4.05E−06	1.33E−14	4.83E−12	–	–
	Pb	4.76E−04	9.23E−04	4.30E−05	1.37E−07	4.26E−17	8.25E−15	–	–	1.23E−06	2.05E−16	7.43E−14	–	–
Scenario B	As	2.56E−03	3.82E−03	1.98E−03	6.33E−06	3.99E−16	7.73E−14	–	–	–	–	–	5.70E−06	6.28E−12
	Cd	1.04E−03	2.11E−03	4.16E−04	8.07E−05	2.14E−16	4.14E−14	–	–	–	–	–	7.26E−05	1.46E−11
	Cr	2.92E−02	4.62E−02	2.69E−02	4.50E−06	2.77E−15	5.36E−13	–	–	–	–	–	4.05E−06	1.36E−10
	Pb	4.76E−04	9.23E−04	4.30E−05	1.37E−06	4.26E−17	8.25E−15	–	–	–	–	–	1.23E−06	1.23E−12
Scenario C	As	2.56E−03	3.82E−03	1.98E−03	6.33E−06	3.99E−16	1.40E−12	–	–	–	–	–	–	–
	Cd	1.04E−03	2.11E−03	4.16E−04	8.07E−05	2.14E−16	4.14E−13	–	–	–	–	–	–	–
	Cr	2.92E−02	4.62E−02	2.69E−02	4.50E−06	2.77E−15	1.09E−08	–	–	–	–	–	–	–
	Pb	4.76E−04	9.23E−04	4.30E−05	1.37E−06	4.26E−17	8.26E−14	–	–	–	–	–	–	–
Scenario D	As	–	–	–	–	–	–	6.33E−06	6.97E−12	–	–	–	–	–
	Cd	–	–	–	–	–	–	8.07E−05	1.62E−11	–	–	–	–	–
	Cr	–	–	–	–	–	–	4.50E−06	1.51E−10	–	–	–	–	–
	Pb	–	–	–	–	–	–	1.37E−06	1.36E−12	–	–	–	–	–

Table 6
The comparison of population risks of various scenarios.

Category	Process													Total population risk	Average individual risk
	Ash treatment plant			First-application					Post-application						
	Laborer in the storage of bottom ash	Laborer in the treated process	Laborer in the storage of treated ash	Laborer	Resident in working duration	Resident in usage duration	Laborer in the landfill	Resident near landfill	Laborer	Resident in working duration	Resident in usage duration	Laborer in the landfill	Resident near landfill		
Scenario A	1.33E−01	1.06E+00	5.88E−02	1.16E−03	5.66E−10	1.10E−07	0.00E+00	0.00E+00	1.05E−02	1.49E−08	5.42E−06	0.00E+00	0.00E+00	1.26E+00	5.89E−07
Scenario B	1.33E−01	1.06E+00	5.88E−02	1.16E−02	5.66E−10	1.10E−07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.42E−03	2.66E−05	1.27E+00	2.54E−06
Scenario C	1.33E−01	1.06E+00	5.88E−02	1.16E−02	5.66E−09	1.80E−02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.28E+00	3.88E−07
Scenario D	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.58E−03	2.96E−05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.61E−03	9.54E−09

sources, receptors, contaminants and exposure pathways so that optimal policies and management strategies may be determined or designed.

4. Conclusion

An LCRA methodology was proposed in this study. Conventional risk assessment focuses largely on assessment of individual and independent sources. The evaluation of policies or strategies requires consideration of interrelated sources and activities; therefore a risk assessment performed in the life cycle framework is desired. By calculating and population risks, associated various receptors resulting from a source at each life stage and aggregating population risks along the life cycle, we obtain total risks.

The total population risks as well as information of individual risk at each stage and average individual risk for various alternative strategies can be used to rank the alternatives and identify important factors for risk management. The case study shows: (1) the duration of pavement by bottom ash is an important management factor; a shorter duration produces less risk to the residents; (2) the laborers receive larger risk than the residents and the significant exposure pathways are inhalation and dermal contact of Cr and Cd. (3) The laborers in the ash treatment plant receive the greatest risk when the policy move from landfill to reuse of the bottom ash. Although this causes the total risk of ash reuse larger than that of landfill, the risk shift from laborers and residents near the landfill to the laborers in the ash treatment stage makes the risk easier to be controlled because the size of exposed population becomes smaller. It is therefore important to characterize the risk shift in terms of not only the magnitude of risk but also the size of exposure and the nature of the sources and receptors. In this study, uncertainty was not analyzed completely due to a larger scope of LCRA. The limitations of this case study arise principally from the assumption of scenarios, such as the treatment processes of bottom ash before reuse and final disposal, the pavement structure, and the considered substances and species. In the future, a proper uncertainty analysis should be incorporated to strengthen the information that can be provided by LCRA.

In sum, the LCRA has important merits potentially over the other risk-related assessment approaches. Compared with traditional individual RA, LCRA can detect risk shift between sources; compared with risk-based LCA, it has better considerations of site-specificity and can distinguish between groups of receptors. These merits make LCRA useful for a comprehensive assessment of strategic alternatives.

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