Vietnam Journal of Science and Technology
DOI: https://doi.org/10.15625/2525-2518/22539

Metal composition and radioactive activity in bottom ash from waste-to-energy plants: Supporting circular economic development

Khuat Thi Hong[1,2,*], Nguyen Thi Hoa[1,3,*], Ngo Tra Mai[1,4], Van Huu Tap[5], Bui Minh Hue[1], Nghiem Thi Ha Lien[1], Nguyen Duc Toan[1],Nguyen Thi Thuy Hang[1,4], Nguyen Dac Truong Giang[3,6], Nguyen Duc Hung[6], Bui Thi Kim Anh[7], Cu Thi Sang[2,8]

[1]*Institute of Physics, Vietnam Academy of Science and Technology, 18 Hoang Quoc Viet, Nghia Do Ward, Ha Noi, Viet Nam*
[2]*VNU School of Interdisciplinary Sciences and Arts, Vietnam National University, 144 Xuan Thuy, Cau Giay Ward, Ha Noi, Viet Nam*
[3]*Thuy Loi University, 175 Tay Son, Kim Lien Ward, Ha Noi, Viet Nam*
[4]*Graduate University of Science and Technology, Vietnam Academy of Science and Technology,18 Hoang Quoc Viet, Nghia Do Ward, Ha Noi, Viet Nam*
[5]*Center for Advanced Technology Development, Thai Nguyen University, Tan Thinh, Thai Nguyen, Viet Nam*
[6]*Thang Long Environmental Technology Consulting and Transfer Co., Ltd, 164 Khuat Duy Tien, Thanh Xuan Ward, Ha Noi, Viet Nam*
[7]*Institute of Science and Technology for Energy and Environment, Vietnam Academy of Science and Technology, 18 Hoang Quoc Viet, Nghia Do Ward, Ha Noi, Viet Nam*
[8]*Electric Power University (EPU), 235 Hoang Quoc Viet, Nghia Do Ward, Ha Noi, Viet Nam*

[*]Emails: 1. *kthong@iop.vast.vn;* 2. *nthoa@iop.vast.vn*

Received: 11 March 2025; Accepted for publication: 5 June 2025

Abstract. Eight bottom ash samples collected from the Soc Son Waste-to-Energy Plant were analyzed to investigate their composition, heavy metal content and radioactive activity, in support of circular economy development aimed at establishing a closed-loop system for municipal solid waste treatment. The structural morphology of the ash samples was examined using Scanning Electron Microscopy (SEM), while X-ray Fluorescence (XRF) spectroscopy was employed to determine the chemical composition. Heavy metals and hazardous components were identified following the US EPA 1311 and SMEWW 3125B:2012 methods. The radioactive activity of natural isotopes, including ^{226}Ra, ^{232}Th, and ^{40}K, was measured using a High-Purity Germanium (HPGe) gamma spectrometer with low background resolution. The results revealed that the primary components of the bottom ash are SiO_2, CaO, Al_2O_3, and Fe_2O_3, accounting for over 60 %, with the remainder consisting of Na, K oxides and various metals. Leaching tests indicated that the concentrations of heavy metals such as As, Cu, Zn, Ni, Cd, Pb and other metals were significantly below the thresholds established in QCVN 07:2009/BTNMT. Furthermore, although radioactive isotopes were present in the bottom ash, their natural radioactive activity was low, with all activity levels well within the safety limits specified in QCVN 05:2008/BXD, Viet Nam Construction Standards.

UNCORRECTED PROOF

Keywords: heavy metals, radioactivity, bottom ash, Soc Son waste-to-energy plant.

Classification numbers: 3.3.2.

1. INTRODUCTION

Waste-to-energy incineration is considered one of the most effective solutions for solid waste treatment, recycling and energy recovery. However, this process generates several by-products, including approximately 20-25 % bottom ash and 1-3 % fly ash, which contain harmful inorganic and organic compounds, particularly heavy metals that cannot be degraded or destroyed. These heavy metals are instead transferred to the by-products generated during the incineration process [1, 2]. Rather than considering bottom ash as waste to be landfilled, numerous studies worldwide have explored the potential of utilizing bottom ash as a resource in the production of construction materials [3]. Bottom ash has been applied in the production of lightweight aggregates for concrete additives in road construction materials and, particularly, as coarse aggregates in the production of Portland cement, the most widely used construction material globally [4–6]. These studies have demonstrated that bottom ash from municipal solid waste incineration is rich in silicon, calcium, aluminum, iron, and sulfur, elements that can partially replace raw materials in cement kilns [7–9].

However, one of the major challenges in enhancing the reuse of bottom ash is the potential leaching of heavy metals when exposed to rainwater, surface water or groundwater, which can lead to environmental contamination [10]. In addition, bottom ash may contain natural radioactive isotopes, such as ^{238}U (^{226}Ra), ^{232}Th (^{228}Ra), and ^{40}K, which originate from the mineral components, organic matter, and construction materials in the waste and tend to concentrate in the ash after the combustion process [11–13]. These radioactive isotopes can remain in the bottom ash after combustion and pose health risks if not properly managed. According to current knowledge, there are no studies evaluating the impact of radiation from bottom ash from municipal solid waste incinerators on human health. However, studies on bottom ash from coal-fired power plants have shown that the radiation levels in the bottom ash are low, with an annual effective dose of radiation below 1 mSv/year, which is within the safety limits recommended by the ICRP. For example, studies by Fidanchevski *et al.* [14] and Badya *et al.* [15] indicate that radiation levels in bottom ash from power plants in North Macedonia and Egypt are low, but the reuse of bottom ash must comply with environmental safety regulations. Therefore, to facilitate the use of bottom ash in the production of construction materials, it is crucial to assess factors such as heavy metal content and radioactive activity in the ash, in order to ensure its safety and acceptance by the community.

In Viet Nam, studies on the reuse of bottom ash are still in the early stages, primarily focusing on its application as a construction material or preliminary research on the heavy metal composition in fly ash from municipal waste incinerators. Research on radioactive activity has predominantly been applied to coal, ash from coal-fired power plants, or naturally occurring materials [16, 17]. To date, no studies have simultaneously evaluated both heavy metals and radioactive activity in bottom ash from waste incineration plants [18–21]. Currently, Viet Nam lacks specific standards or regulations regarding the use of bottom ash, and most of the ash is utilized as backfill material or in small-scale construction applications. Simultaneous assessment of both heavy metal content and radioactivity in bottom ash is important in fully identifying potential risks to human health and the environment, thereby providing a scientific basis for developing technical regulations and promoting safe application in the circular

UNCORRECTED PROOF

economy. Therefore, more comprehensive research on these factors is essential to ensure the safe and sustainable development of a circular economy.

2. MATERIALS AND METHODS

2.1. Materials

Bottom ash samples were collected from the Soc Son Waste-to-Energy Plant, the largest municipal waste incineration power plant in Viet Nam, which is currently operating stably. The plant uses Belgian mechanical grate technology with five independent incinerators, each equipped with a separate bottom ash discharge gate.

Sampling was conducted in two phases, in December 2023 and June 2024, to assess the temporal stability of metal composition and radioactivity, as well as the influence of seasonal variation. Samples were taken from three incinerators operating under stable conditions to reflect differences in operational parameters. Additionally, a composite sample was collected from the central storage area, where ash from the three incinerators is temporarily accumulated, representing the typical mixed ash managed at the facility.

This study focuses on municipal solid waste (MSW) bottom ash due to its dominance in Viet Nam's waste stream and its relevance to current waste-to-energy practices. Unlike industrial waste, which is typically more homogeneous, MSW in Viet Nam is highly heterogeneous-containing 40-60 % food waste along with plastics, paper, metals, textiles, and inorganic materials-resulting in more complex and variable ash characteristics. Additionally, the incineration of mixed waste containing plastics and metals can generate soluble metal chlorides, further increasing the risk of contamination when bottom ash is reused in construction materials. Although studies on metal content in MSW ash exist, data on leaching behavior and radioactivity remain scarce [18, 22].

Detailed sample information is provided in Table 1.

Table 1. Summary of bottom ash sample information collected from Soc Son Waste-to-Energy plant.

No.	Sampling Location	Sample Code
1	Discharge Gate 1	BA1.1
2	Discharge Gate 2	BA1.2
3	Discharge Gate 3	BA1.3
4	Storage Area	BA1.4

2.2. Methods

This study used modern analytical equipment, including scanning electron microscope (SEM) model SU3500 from Hitachi (Japan) and XRF analysis equipment (PANalytical Axios mAX) from the Institute of Physics, Vietnam Academy of Science and Technology. These tools were used to analyze the chemical composition, structural properties, particle size, and to determine the specific radioactive activity of natural radioactive isotopes present in the bottom ash from the waste-to-energy incineration plant. SEM was used to observe the surface morphology of the bottom ash, while its chemical composition was determined using X-ray fluorescence (XRF) spectroscopy. The energy-dispersive X-ray spectroscopy (EDS) technique

UNCORRECTED PROOF

was not applied in this study and will be considered in future research to supplement data on the elemental composition of the sample surface.

2.3. Theoretical background

2.3.1. Metal composition and surface morphology analysis of bottom ash

The scanning electron microscopy (SEM) imaging technique is employed to study the shape and particle size of bottom ash from the municipal solid waste incineration plant. X-ray fluorescence (XRF) spectroscopy is used to determine the chemical composition of the bottom ash. Hazardous components in the leachate from the bottom ash are identified using the US EPA 1311 method (Toxicity Characteristic Leaching Procedure - TCLP) and SMEWW 3125B:2012 (Standard Methods for the Examination of Water and Wastewater). Specifically, the US EPA 1311 method helps determine the solubility of heavy metals and other hazardous compounds in the leachate, while SMEWW 3125B:2012 is used to analyze chemical parameters in the water sample. To perform these analyses, the PANalytical AXIOS FAST X-ray Fluorescence (XRF) spectrometer is used for the chemical composition analysis, while the Thermo Fisher Scientific iCAP 7000 is used for water analysis according to SMEWW standards. The concentration of heavy metals in the leachate is compared with the national technical regulation QCVN 07:2009/BTNMT.

2.3.2. Radioactive activity determination method

The radioactive activity of the isotopes ^{226}Ra, ^{232}Th, and ^{40}K in the bottom ash samples is determined through gamma spectrum analysis and relative calculations using standard samples RGU-1, RGTh-1, and RGK-1 from the International Atomic Energy Agency (IAEA). Specifically, the bottom ash samples are dried, finely ground, and placed in sealed containers for approximately four weeks prior to gamma measurements. This step is necessary to prevent the loss of radon gas and to ensure radioactive equilibrium between the parent isotopes and their daughter isotopes in the uranium and thorium decay chains.

To record the gamma spectrum, a low-background gamma spectrometer system from the Institute of Physics, Vietnam Academy of Science and Technology, is used. The gamma spectrometer is equipped with a high-purity germanium (HPGe) detector, model GEM20P4-70 from ORTEC, and the GammaVision software is utilized for gamma spectrum analysis. This system has an absolute efficiency of 20 % compared to a NaI (Tl) scintillation detector (3x3 inches) and an energy resolution of 1.9 keV at the 1.332 keV peak of a ^{60}Co source. The radioactive activity of ^{226}Ra is evaluated based on the photopeaks at 295.57 keV and 351.90 keV emitted from ^{214}Pb, as well as the photopeak at 609.3 keV emitted from ^{214}Bi. The radioactive activity of ^{232}Th is assessed from the photopeaks at 338.6 keV and 911.1 keV emitted from ^{228}Ac. The radioactive activity of ^{40}K is directly calculated from the 1460 keV photopeak.

A blank sample was used during the measurement to eliminate background signals and ensure the accuracy of the results. This blank sample helps determine the background radioactivity level, thereby clearly distinguishing the radioactivity of target isotopes in bottom ash samples.

To ensure statistical accuracy, the specific radioactive activity of ^{226}Ra, ^{232}Th, and ^{40}K is determined by calculating the average values [23].

$$Cj = Cj(tb) + \Delta j(tb) \quad (1)$$

UNCORRECTED PROOF

with Cj(tb) is the average specific radioactive activity: Cj(tb) = $\frac{1}{n}\sum_{i=1}^{n} Cj(i)$, where i = 1, 2, …, n and n is the number of samples measured; j represents the radioactive isotopes.

Δj(tb) is the mean square deviation:

$$\Delta j(tb) = \sqrt{\frac{\sum_{i=1}^{n}\left[C_j(i) - C_j(tb)\right]^2}{n-1}} \quad (2)$$

The criteria for evaluating the safety levels of radioactive activity in construction materials, as specified in QCVN 05:2008/BXD of Viet Nam, are calculated using the following formulas:

- For house construction: $I_1 = C_{Ra}/300 + C_{Th}/200 + C_K/3000$.

- For outdoor construction projects: $I_2 = C_{Ra}/700 + C_{Th}/500 + C_K/8000$.

- For backfilling: $I_3 = C_{Ra}/2000 + C_{Th}/1500 + C_K/20000$.

Where the safety radioactive activity index (I) is an indicator that reflects the total radioactive activity from the individual natural radioactive activities of C_{Ra}, C_{Th}, and C_K in the material; C_{Ra}, C_{Th}, and C_K are the specific radioactive activities of the isotopes ^{226}Ra, ^{232}Th, and ^{40}K measured in Bq/kg.

3. RESULTS AND DISCUSSION

3.1. Morphological characteristics and heavy metal composition in bottom ash

SEM analysis was conducted to examine the surface morphology and structure of the bottom ash particles from the municipal solid waste incineration plant. The SEM images of the bottom ash samples reveal that the particles exhibit a porous and loose structure. The individual particles are irregularly shaped, with numerous edges and angles, and rough surfaces, with only a few spherical particles observed. The non-uniform shape and rough surface texture of the bottom ash particles reduce adhesion both among the particles themselves and with other materials. This could impact the strength of the final product if the bottom ash is used to replace a portion of the aggregate in concrete or mortar. Therefore, if bottom ash is used as a replacement aggregate in concrete or mortar, these non-uniform geometrical characteristics can negatively affect the physical and mechanical properties of the final product. Screening and particle size classification prior to use is necessary to improve dispersibility and uniformity in construction material applications.

In addition, the morphology observed from SEM images reflects a close relationship with the chemical composition of bottom ash. Specifically, the predominance of oxides such as SiO_2 and Al_2O_3 - which are often derived from inorganic mineral materials such as sand, glass and ceramics - may contribute to the irregular shape and rough surface of the particles. At the same time, the high CaO content, which originates from calcium-rich organic materials such as paper and food, may be related to the porous structure, strong reaction in alkaline environments and influence the chemical activity when used as an additive for cement. These correlations suggest that the combined evaluation of morphological analysis and chemical composition is essential to clarify the material properties and guide the effective application of bottom ash in the construction industry.

UNCORRECTED PROOF

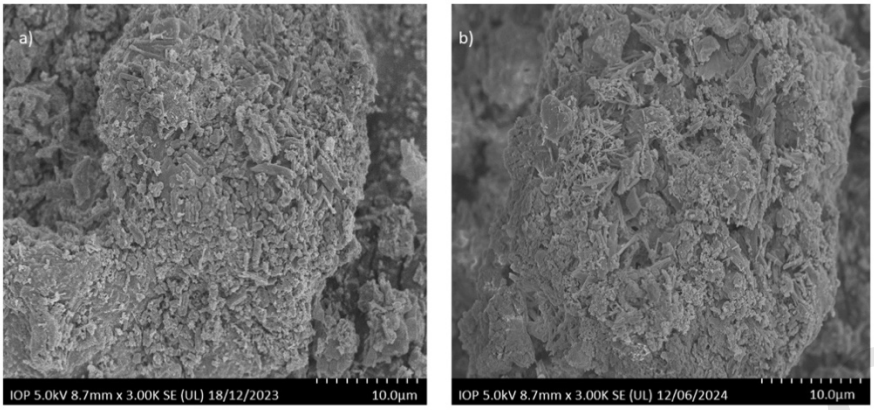

Figure 1. SEM images showing the particle size distribution of bottom ash from the municipal solid waste incineration plant: Phase 1 (a) and Phase 2 (b).

Table 2. Main chemical composition in the bottom ash samples (%).

Composition	Phase 1 (December 2023)					Phase 2 (June 2024)				
	BA1.1	BA1.2	BA1.3	BA1.4	TB1	BA2.1	BA2.2	BA2.3	BA2.4	TB2
SiO_2	40.2	39.7	40.54	41.68	40.53	39.51	43.05	40.34	39.18	40.52
CaO	13.13	16.67	21.45	18.11	17.34	23.69	22.36	21.81	19.82	21.92
K_2O	4.13	4.67	4.65	5.39	4.71	3.49	5.05	4.26	4.79	4.40
Na_2O	8.34	5.61	6.03	4.17	6.04	3.32	5.47	3.69	4.05	4.13
Fe_2O_3	5.57	8.41	5.08	5.3	6.09	5.68	5.82	6.19	5.24	5.73
MgO	2.13	1.02	0.87	0.75	1.19	1.03	1.24	1.68	2.53	1.62
Al_2O_3	13.75	11.52	13.57	8.93	11.94	12.23	8.29	13.52	14.13	12.04
Sb_2O_3	0.27	0.14	KPH	0.32	0.18	KPH	0.45	KPH	KPH	0.11
TiO_2	0.29	0.75	0.24	0.36	0.41	0.65	0.7	0.69	1.15	0.80
ZnO	3.17	3.58	1.48	3.65	2.97	3.46	1.94	1.11	3.95	2.615
PbO	0.66	0.51	0.73	0.83	0.68	0.91	0.37	0.53	0.34	0.54
CuO	0.21	0.24	0.56	0.39	0.35	0.34	0.18	0.27	0.36	0.29
Cl	4.7	3.15	2.22	5.63	3.93	2.35	2.11	3.81	2.05	2.58
Br	0.6	0.41	0.4	0.76	0.54	0.54	0.3	0.3	KPH	0.29
SO_3	3.3	3.05	2.05	3.56	2.99	2.47	1.45	1.17	2.18	1.82
P_2O_3	KPH	0.34	0.24	0.39	0.24	0.46	0.87	0.53	0.63	0.62

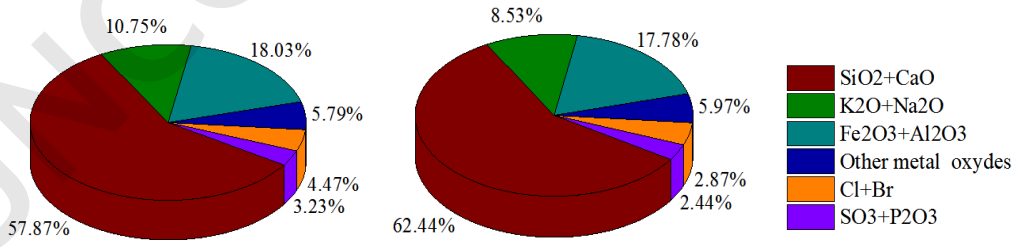

Figure 2. Average elemental composition of bottom ash samples from municipal solid waste incineration: Phase 1 (a) and Phase 2 (b).

UNCORRECTED PROOF

The results of the bottom ash composition analysis are presented in Table 2 and Figure 2. The main components of all the bottom ash samples are SiO_2 and CaO, which together account for more than 50 % of the total composition. Among these, SiO_2 is the predominant component (30-40 %), primarily associated with inorganic materials such as glass, sand and ceramics in the waste incineration process. A smaller proportion consists of CaO (13-23 %), which mainly results from the incineration of waste containing lime-based compounds, such as paper, plastics and food. The SiO_2 content in the samples collected during Phase 1 (winter) is similar to that in Phase 2 (summer), while the CaO content is significantly lower. This reduction can be attributed to seasonal variations in waste composition: in summer, the amount of food waste tends to decrease due to faster biodegradation and better pre-sorting before treatment, resulting in lower input of calcium-containing materials (e.g., eggshells, bones, paper, and food leftovers) into the incinerator compared to winter. The content of Al_2O_3 (8-15 %) and Fe_2O_3 (5-8 %) also constitutes a relatively high proportion of the bottom ash. It can be observed that the primary components of the bottom ash from municipal solid waste incineration are metals and minerals [24].

The bottom ash samples analyzed all contain a certain amount of Cl^-, ranging from 2-5 %. Plastics, particularly PVC (Polyvinyl chloride), contribute to the increased Cl^- content in the bottom ash. The samples also contain small amounts of MgO, ZnO, PbO, CuO and TiO_2, while Sb_2O_3 was detected in some samples. Heavy metal oxides such as Cr, Cd, and Ni are almost absent due to their low concentrations or complete absence in the samples. The composition of the bottom ash from the Soc Son Waste-to-Energy Plant's municipal solid waste incineration, for both survey phases, is presented in Figure 3, along with the bottom ash compositions of China, Portugal, France, and Italy [25–28].

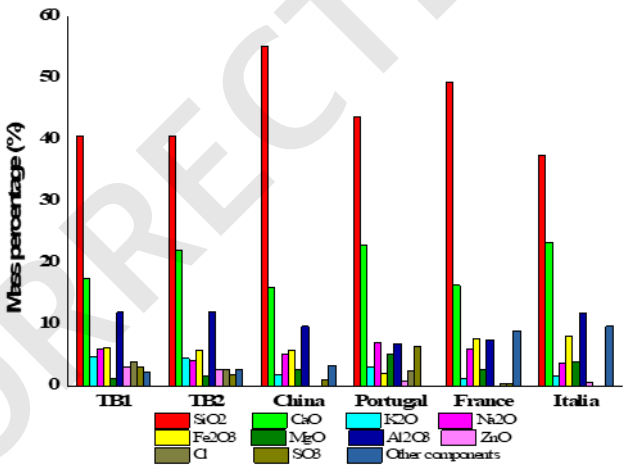

Figure 3. Comparison of major components in bottom ash produced at the Soc Son Waste-to-Energy Plant (Viet Nam) with China, Portugal, France and Italy.

The analysis of the bottom ash composition from samples collected at the Soc Son Waste-to-Energy Plant, Viet Nam (TB1 and TB2), compared with samples from China, Portugal, France, and Italy, reveals that the primary components of the bottom ash are mainly oxides of Si, Ca, Al, and Fe. The SiO_2 content in samples TB1 and TB2 averages around 40 %, which is lower than that of China (55.2 %) but comparable to Portugal (43.75 %) and France (49.3 %). SiO_2 is an important component for forming the material structure and maintaining stability across the different samples. The CaO content in TB1 (17.34 %) and TB2 (21.92 %) is similar

UNCORRECTED PROOF

to Portugal (22.77 %) and Italy (23.29 %), and higher than that of China (15.9 %), contributing to the improved construction properties of the material, as CaO is a key component of cement. This difference in composition may be due to the fact that the input waste at Soc Son primarily consists of mixed, unseparated waste, while other countries use waste that has been pre-sorted.

The K_2O and Na_2O contents in TB1 and TB2 are higher than those in the foreign samples (K_2O: 4.71 % and 4.40 %, Na_2O in TB1: 6.04 %), which may affect the chemical properties of the recycled ash, as these salts are highly soluble and prone to causing corrosion. The Fe_2O_3 content in TB1 and TB2 is moderate (6.09 % and 5.73 %), similar to that of China (5.7 %) and France (7.6 %), but higher than that of Portugal (2.03 %). The Al_2O_3 content in TB1 and TB2 is relatively high (11.94 % and 12.04 %), exceeding that of Portugal (6.81 %) and France (7.5 %). Unsorted mixed waste may be the cause of the increased Al_2O_3 and Fe_2O_3 content in the bottom ash from the Soc Son Waste-to-Energy Plant, as impurities from various sources are not removed before combustion. Additionally, the Cl and SO_2 contents in TB1 and TB2 are higher than those in the foreign samples, which could potentially lead to corrosion and reduce the strength of concrete when the ash is recycled.

The difference in the composition of bottom ash indicates that waste sorting is a crucial factor that affects the chemical composition of the ash and should be taken into account when comparing results between countries.

Table 3. Results of the leaching test of bottom ash from municipal solid waste incineration (mg/L).

Component Element	Batch 1 (12/2023)				Batch 2 (06/2024)				QCVN 07:2009/ BTNMT
	BA1.1	BA1.2	BA1.3	BA1.4	BA2.1	BA2.2	BA2.3	BA2.4	
pH	9.8	11.1	10.6	10.2	10.9	10.7	10.4	10.1	-
Sb	0.07	0.01	0.06	0.01	0.02	0.02	KPH	KPH	1
As	0.02	0.03	KPH	0.03	0.02	0.07	0.03	0.04	2
Ba	73	55	15	63	67	43	3.1	17	100
Co	KPH	0.08	KPH	7	7.24	0.001	KPH	KPH	80
Mn	KPH	KPH	KPH	KPH	KPH	KPH	KPH	KPH	-
Hg	0.0008	KPH	0.0024	0.0006	0.003	0.0005	0.0005	0.0016	0.2
Mo	2.2	4	2.4	1.3	1.6	3.3	1.9	3.3	350
Na	1024	675	724	538	684	774	403	926	-
Ag	0.1	KPH	0.04	0.02	0.06	0.02	0.01	0.01	5
Se	KPH	0.04	KPH	0.03	0.02	0.03	0.05	0.04	1
Va	KPH	KPH	KPH	KPH	KPH	KPH	KPH	KPH	25
Pb	< 0.05	0.08	0.005	< 0.05	< 0.05	< 0.05	< 0.05	0.07	15
Zn	58	18	8	80	26	17	20	10	250
Cu	5.8	1.7	3.5	4.5	2.2	2.8	1	1.8	-
Ni	KPH	KPH	KPH	KPH	KPH	KPH	KPH	KPH	70
Cr	KPH	0.05	KPH	0.06	0.2	KPH	0.18	0.16	5
Cd	0.07	0.02	0.1	0.01	0.005	0.12	0.01	0.04	0.5
Cl^-	437	241	416	347	421	262	288	307	-
F^-	0.24	0.31	0.54	0.25	0.03	0.07	0.39	0.27	180

Note: KPH: Not detected.

UNCORRECTED PROOF

Table 3 presents the results of the leaching test for eight bottom ash samples collected from different locations across two survey batches. Toxic heavy metals such as Hg, As, Cd, Cu, Pb, and Zn were detected in the bottom ash samples; however, their concentrations were not uniform. Despite being collected from the same waste incineration plant, the variability in these samples may be attributed to differences in the source of the incinerated waste and natural fluctuations in the composition of municipal solid waste. All of these toxic heavy metals were found to have concentrations within the safe limits specified by QCVN 07:2009/BTNMT: National Technical Regulation on Hazardous Waste Thresholds.

Some elements, such as Mn, Sb, Cr, Sn, V, Se, and Ni, were not detected in certain samples, which may indicate that the concentrations of these substances are either very low or nonexistent in the bottom ash. Most of the toxic heavy metals, especially those with valences of II and III, are influenced by the pH of the environment. As a result, the leaching of these metals is highly affected by natural weather conditions. Some metals can be retained in mineral phases such as calcite, ettringite, aluminosilicates, and oxides, which helps reduce the release of heavy metals. Therefore, the bottom ash from the municipal solid waste incineration plant can meet environmental protection requirements.

The pH of the leachate samples is relatively high, ranging from 9.8 to 11.1, indicating an alkaline environment in the leachate solution. A high pH can activate pozzolanic reactions, allowing the bottom ash to react with $Ca(OH)_2$ in cement to form calcium silicate hydrate (C-S-H) compounds. These compounds contribute to the increased mechanical strength of concrete or bricks. The high alkalinity also helps reduce the corrosion of reinforcement steel in concrete by creating an alkaline environment that protects the steel surface. However, it may cause cracking, swelling, or expansion of construction materials when free CaO reacts with water to form $Ca(OH)_2$. This presents particular risks for applications such as non-fired bricks or concrete. In cases where bricks or concrete containing bottom ash are exposed to rain or groundwater, the high pH of the leachate may increase the solubility of certain toxic substances (e.g., Pb, As, Zn), potentially compromising environmental safety and public health [29].

The elevated concentration of sodium (Na) in the leaching solution, which ranges from 403 to 1024 mg/kg, can be attributed primarily to the constituents of household waste. This waste typically contains significant amounts of excess food, which is rich in salts and seasonings, as well as various hygiene products that are readily soluble. Furthermore, the concentration of chloride ions (Cl^-) in the leaching solution from both survey batches was notably high, with values fluctuating between 262 mg/kg and 437 mg/kg. The study by Kicínska *et al.* [30] and other research [31, 32] also show that components such as chloride in bottom ash can pose a potential risk to the environment if not properly treated. The presence of sodium (Na^+) and chloride (Cl^-) ions poses a potential risk for groundwater contamination and may adversely affect the durability of bottom ash when utilized as a raw material in construction applications. Consequently, it is imperative that pre-treatment strategies are employed to mitigate the chloride content in bottom ash prior to its incorporation into construction materials. Such strategies may include washing or chemical treatment processes aimed at reducing the Cl^- concentration effectively.

3.2. Radioactivity

The results of the specific radioactivity measurements and the calculation of the radioactivity indices for the bottom ash samples collected from the Soc Son Waste-to-Energy Plant in two survey batches are presented in Table 4.

UNCORRECTED PROOF

Table 4. Results of specific radioactivity measurements and radioactivity index calculations for bottom ash samples.

Radioactive nuclei (j)	^{226}Ra	^{232}Th	^{40}K	Radioactive nuclei (j)	^{226}Ra	^{232}Th	^{40}K
BA1.1	35.2 ± 8.0	29.3 ± 6.8	391.0 ± 78.0	BA2.1	31.8 ± 7.2	29.7 ± 6.6	381.0 ± 76.0
BA1.2	33.9 ± 7.8	31.1 ± 7.1	396.0 ± 78.0	BA2.2	31.5 ± 7.1	30.6 ± 6.8	386.0 ± 77.0
BA1.3	34.8 ± 8.0	31.5 ± 7.1	397.0 ± 78.0	BA2.3	32.1 ± 7.5	31.9 ± 6.8	383.0 ± 76.0
BA1.4	35.1 ± 8.0	31.9 ± 7.0	393.0 ± 78.0	BA2.4	30.4 ± 7.2	31.1 ± 7.0	387.0 ± 78.0
TB.1	34.75± 7.95	30.95±7.0	394.25± 78.0	TB.2	31.45±7.25	30.825±6.8	384.25±76.75
Cj(tb)	34.75	30.95	394.25	Cj(tb)	31.45	30.825	384.25
$\Delta j(tb)$	0.6	1.1	4.7	$\Delta j(tb)$	0.7	0.9	4.2
Cj	35.3	32.1	399.0	Cj	32.2	31.7	388.5
Safety radioactivity index, I							
I_1	I_1 = 0.411			I_1	I_1 = 0.396		
I_2	I_2 = 0.165			I_2	I_2 = 0.158		
I_3	I_3 = 0.059			I_3	I_3 = 0.057		

According to the data presented in Table 4, the average specific radioactivity levels for the isotope ^{226}Ra were measured at 34.75 ± 7.95 Bq/kg for Batch 1 and 31.45 ± 7.25 Bq/kg for Batch 2. For the isotope ^{232}Th, the average specific radioactivity was recorded as 30.95 ± 7.0 Bq/kg for Batch 1 and 30.825 ± 6.8 Bq/kg for Batch 2. Additionally, the average specific radioactivity for ^{40}K was found to be 394.25 ± 78.0 Bq/kg for Batch 1 and 384.25 ± 76.75 Bq/kg for Batch 2. It is noteworthy that the samples from Batch 1 exhibited higher radioactivity levels compared to those from Batch 2. When these values are compared to the safety radioactivity limits established by QCVN 05:2008/BXD, it is evident that the radioactivity levels in samples from both survey batches are relatively low. Specifically, the safety radioactivity index I_1, which is applicable to large-scale construction materials, was calculated to be 0.411 for Batch 1 and 0.396 for Batch 2, both of which are below the safety threshold of 1. Similarly, the index I_2, relevant for cladding materials, yielded values of 0.165 for Batch 1 and 0.158 for Batch 2, both of which are also below the permissible limit of 1.5. Furthermore, the index I_3, which assesses safety for filling materials, was significantly lower than the prescribed limit. Consequently, it can be concluded that these waste materials are suitable for use in the production of construction materials without contravening radioactivity safety regulations.

Figure 4 shows that the specific radioactivity levels of the isotopes ^{226}Ra, ^{232}Th, and ^{40}K in bottom ash samples obtained from municipal solid waste (MSW) incinerators during two survey periods (TB1 and TB2) were found to be significantly lower than average radioactivity levels observed in coal ash samples. Specifically, the measured radioactivity for ^{226}Ra ranged from 31.45 to 34.75 Bq/kg, for ^{232}Th from 30.83 to 30.95 Bq/kg, and for ^{40}K from 384.25 to 394.25 Bq/kg. These relatively low levels of radioactivity suggest that bottom ash derived from municipal solid waste incineration possesses a more favorable safety profile concerning radiation exposure, thereby mitigating the risk of radiation-related health hazards in construction applications. Furthermore, the findings indicate a greater potential for the reuse of bottom ash as a safer alternative construction material compared to coal ash, which can contribute to a

UNCORRECTED PROOF

reduction in the demand for conventional raw materials. The fly ash samples BAVT, BADH, BAMD, and BAQN represent the survey locations in N.D. Dao (2024) study on the radioactivity of ash from several thermal power plants in Viet Nam, including the Vinh Tan (BAVT), Duyen Hai (BADH), Mong Duong (BAMD), and Quang Ninh (BAQN) power plants.

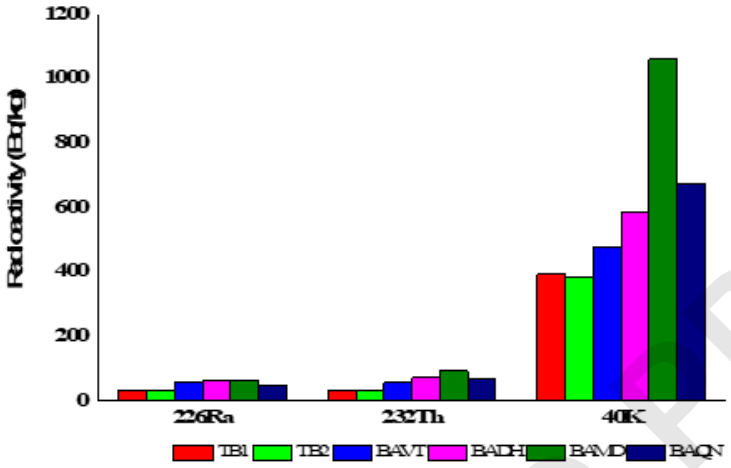

Figure 4. Comparison of the radioactivity of bottom ash samples from municipal solid waste incinerators (MSW) with coal ash samples [23].

4. CONCLUSION AND RECOMMENDATIONS

The study undertook a comprehensive investigation into the surface characteristics, chemical composition, heavy metal leaching behavior, and radioactivity of bottom ash derived from the municipal solid waste incinerator at the Soc Son Waste-to-Energy Plant. Based on the findings obtained from this analysis, the study draws the following key conclusions:

1. *Structural characteristics and composition of bottom ash:* The bottom ash exhibits a porous and irregularly shaped particle structure characterized by a heterogeneous distribution of particle sizes. The primary constituents of the bottom ash include silicon dioxide (SiO_2), calcium oxide (CaO), aluminum oxide (Al_2O_3), and iron oxide (Fe_2O_3), which collectively constitute over 60 % of the total composition. The remaining fraction comprises various oxides, including sodium oxide (Na_2O), potassium oxide (K_2O), and other metal oxides.

2. *Comparison with international bottom ash:* The primary constituents of the bottom ash collected from the Soc Son Waste-to-Energy Plant exhibit a composition that is relatively comparable to bottom ash samples from various countries, including China, France, Portugal and Italy. However, it is important to note that there are variations in the concentrations of individual components across these different geographical contexts. Such differences may be attributed to factors such as the composition of the municipal solid waste processed, the operational conditions of the incineration facilities, and the specific technologies employed in waste-to-energy conversion.

3. *Heavy metal content in bottom ash:* Leaching tests conducted on the bottom ash samples indicated the presence of heavy metals, including arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), nickel (Ni), lead (Pb), and zinc (Zn). Additionally, certain samples exhibited low concentrations of antimony (Sb), chromium (Cr), tin (Sn), vanadium (V) and selenium (Se).

UNCORRECTED PROOF

Notably, all measured concentrations of these heavy metals were found to be below the thresholds established by QCVN 07:2009/BTNMT. This finding suggests that the bottom ash derived from municipal solid waste incineration does not meet the criteria for classification as hazardous waste.

4. *pH of the leachate solution:* The elevated pH levels observed in the leachate samples from the bottom ash indicate a significant degree of alkalinity. This characteristic necessitates appropriate treatment or careful management during utilization to mitigate potential adverse effects on both the environment and structural integrity.

5. *Concentration of Na^+ and Cl^- ions:* The concentrations of Na^+ and Cl^- ions in the leachate from the bottom ash were found to be relatively high. To minimize the risks, pre-treatment measures such as washing or chemical treatment (lime, additives) should be applied to reduce chloride and sodium concentrations, ensuring the quality of construction materials and preventing groundwater contamination.

6. *Radioactivity:* The levels of natural radioactivity and the calculated safety radioactivity indices for the bottom ash derived from municipal solid waste (MSW) incinerators are significantly lower than the safety thresholds established for building materials as per QCVN 05:2008/BXD. This finding indicates that there are no restrictions on the reuse or recycling of this waste material.

7. *Specific radioactivity:* The specific radioactivity levels of isotopes ^{226}Ra, ^{232}Th, and ^{40}K in bottom ash derived from municipal solid waste (MSW) incinerators are significantly lower than those found in coal ash. This observation suggests that bottom ash from MSW incinerators possesses a greater potential for reuse as a safer construction material compared to coal ash. The lower radioactivity levels indicate that the environmental and health risks associated with the use of bottom ash in construction applications are minimized, making it a more favorable option for sustainable building practices.

The research underscores the potential of bottom ash as a valuable recycling material within the framework of a circular economy. The utilization of bottom ash in construction materials has been demonstrated to be safe, with no restrictions imposed by concerns related to radioactivity or heavy metal leaching. Nonetheless, it is crucial to address specific factors such as water absorption during the manufacturing process and to implement pre-treatment measures aimed at reducing chloride ion (Cl^-) content. These considerations are essential to mitigate any potential risks that could adversely affect the durability of construction materials derived from bottom ash resulting from municipal solid waste (MSW) incineration.

Acknowledgments: Khuat Thi Hong was funded by the Master, PhD Scholarship Programme of Vingroup Innovation Foundation (VINIF), code VINIF.2023.TS.034.

CRediT authorship contribution statement. Khuat Thi Hong: Methodology, Investigation, Writing – review & editing. Nguyen Thi Hoa: Writing – review & editing. Ngo Tra Mai, Van Huu Tap: Supervision, Writing – original draft. Bui Minh Hue, Nghiem Thi Ha Lien, Nguyen Duc Toan: Formal analysis. Nguyen Thi Thuy Hang, Nguyen Dac Truong Giang, Nguyen Duc Hung, Bui Thi Kim Anh, Cu Thi Sang: Resources.

Declaration of competing interest. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

UNCORRECTED PROOF

REFERENCES

1. Quina M. J., Bontempi E., Bogush A., Schlumberger S., Weibel G., Braga R., Funari V., Hyks J., Rasmussen E., Lederer J. – Technologies for the management of MSW incineration ashes from gas cleaning: New perspectives on recovery of secondary raw materials and circular economy. Sci. Total Environ., 635 (2018) 526–542. https://doi.org/10.1016/j.scitotenv.2018.04.150.
2. Wang P., Hu Y., Cheng H. – Municipal solid waste (MSW) incineration fly ash as an important source of heavy metal pollution in China. Environ. Pollut., 252 (2019) 461–475. https://doi.org/10.1016/j.envpol.2019.04.082.
3. Reijnders L. – The cement industry as a scavenger in industrial ecology and the management of hazardous substances. J. Ind. Ecol., 11 (2007) 15–25. https://doi.org/10.1162/jiec.2007.997.
4. Müller U., Rübner K. – The microstructure of concrete made with municipal waste incinerator bottom ash as an aggregate component. Cem. Concr. Res., 36 (2006) 1434–1443. https://doi.org/10.1016/j.cemconres.2006.03.023.
5. Rübner K., Haamkens F., Linde O. – Use of municipal solid waste incinerator bottom ash as aggregate in concrete. Q. J. Eng. Geol. Hydrogeol., 41 (2008) 459–464. https://doi.org/10.1144/1470-9236/07-036.
6. Ma G. F., Onitsuka K., Negami T. – Utilizations of incineration ash from municipal solid waste as admixtures for road embankment materials. Geotech. Eng., 38 (2007) 87–94.
7. Nidheesh P. V., Suresh Kumar M. – An overview of environmental sustainability in cement and steel production. J. Clean. Prod., 231 (2019) 856–871. https://doi.org/10.1016/j.jclepro.2019.05.251.
8. Yin K., Ahamed A., Lisak G. – Environmental perspectives of recycling various combustion ashes in cement production – a review. Waste Manag., 78 (2018) 401–416. https://doi.org/10.1016/j.wasman.2018.06.012.
9. Zhao Y., Zhan J., Liu G., Ren Z., Zheng M., Jin R., Yang L., Wang M., Jiang X., Zhang X. – Field study and theoretical evidence for the profiles and underlying mechanisms of PCDD/F formation in cement kilns co-incinerating municipal solid waste and sewage sludge. Waste Manag., 61 (2017) 337–344. https://doi.org/10.1016/j.wasman.2016.12.008.
10. Huber F., Fellner J. – Integration of life cycle assessment with monetary valuation for resource classification: The case of municipal solid waste incineration fly ash. Resour. Conserv. Recycl., 139 (2018) 17–26. https://doi.org/10.1016/j.resconrec.2018.08.003.
11. United Nations Scientific Committee on the Effects of Atomic Radiation – Sources and effects of ionizing radiation: UNSCEAR 2000 report, volume I, United Nations, New York (2000).
12. International Atomic Energy Agency – Application of the concepts of exclusion, exemption and clearance, IAEA, Vienna (2004).
13. Cinelli G., De Cort M., Tollefsen T. – European atlas of natural radiation, Publications Office of the European Union, Luxembourg (2019). https://doi.org/10.2760/520053.
14. Fidanchevski E., Angjusheva B., Jovanov V., Murtanovski P., Vladiceska L., Stamatovska Aluloska N., Krneta Nikolić J., Ipavec A., Šter K., Mrak M., et al. – Technical and radiological characterisation of fly ash and bottom ash from thermal power plant. J. Radioanal. Nucl. Chem., 330 (2021) 685–694. https://doi.org/10.1007/s10967-021-07980-w.
15. Talat L. A., Bady M. F., Hassanien H. M., Kamal El-Deen A. M., Hussein A. M. – Study of solid waste and ashes content of radioactive and heavy metals in Assiut thermal power plant. J. Eng. Sci., 39 (2011) 1335–1342.
16. Dao N. D., Loan T. T. H., Ba V. N. – Evaluation of radioactive activity in coal and ash of some coal-fired thermal power plants in Vietnam. J. Sci. Technol., 7 (2024) 31–39. https://doi.org/10.55401/p73w6w17.
17. Dinh T. K., Luyen T. V. – Investigation of radioactivity in granite-based construction materials. HCMUE J. Sci., 16 (2009) 41–52. https://doi.org/10.54607/HCMUE.JS.0.16.973(2009).
18. Mai N. T., Lap B. Q. – Research on composition and propose ways to use ash and slag from household waste incinerators to generate electricity. J. Sci. Technol. Water Resour. Environ. Eng., 48 (2015) 50–56.

UNCORRECTED PROOF

19. Lan N. C. – Using bottom ash from incineration plants as building materials. Vietnam J. Sci. Technol., 8 (2021) 42–48.
20. Phuoc H. T., Long N. T., Khang L. T., Phieu L. T., Quang L. V. – Research on manufacturing self-compacting concrete bricks for bank protection works using waste ash and slag from incinerators. J. Mater. Constr., 11 (2021) 24–29.
21. Tru V. N., Lam T. V., Cuong H. A., Hung L. N. – Research on using fly ash and bottom slag of Green Star Waste-to-Energy Plant to produce high-strength concrete under laboratory conditions. J. Mater. Constr., 14 (2024) 113–119. https://doi.org/10.54772/jomc.03.2024.675.
22. Giang L. V., Trung L. D., Han H. T. N., Thanh T. – Evaluation of heavy metal content and agricultural reuse potential of domestic waste incineration ash, https://tapchimoitruong.vn/nghien-cuu-23/danh-gia-ham-luong-kim-loai-nang-va-kha-nang-tai-su-dung-trong-nong-nghiep-cua-tro-dot-rac-thai-sinh-hoat-31449 (accessed 10 May 2025).
23. International Atomic Energy Agency – Measurement uncertainty: A practical guide for secondary standards dosimetry laboratories, IAEA, Vienna (2008).
24. Bayuseno A. P., Schmahl W. W. – Understanding the chemical and mineralogical properties of the inorganic portion of MSWI bottom ash. Waste Manag., 30 (2010) 1509–1520. https://doi.org/10.1016/j.wasman.2010.03.010.
25. Lu Y., Tian A., Zhang J., Tang Y., Shi P., Tang Q., Huang Y. – Physical and chemical properties, pretreatment, and recycling of municipal solid waste incineration fly ash and bottom ash for highway engineering: A literature review. Adv. Civ. Eng., 2020 (2020) 1–17. https://doi.org/10.1155/2020/8886134.
26. Cristelo N., Segadães L., Coelho J., Chaves B., Sousa N. R., Lopes M. L. – Recycling municipal solid waste incineration slag and fly ash as precursors in low-range alkaline cements. Waste Manag., 104 (2020) 60–73. https://doi.org/10.1016/j.wasman.2020.01.013.
27. Rendek E., Ducom G., Germain P. – Carbon dioxide sequestration in municipal solid waste incinerator (MSWI) bottom ash. J. Hazard. Mater., 128 (2006) 73–79. https://doi.org/10.1016/j.jhazmat.2005.07.033.
28. Schabbach L. M., Andreola F., Barbieri L., Lancellotti I., Karamanova E., Ranguelov B., Karamanov A. – Post-treated incinerator bottom ash as alternative raw material for ceramic manufacturing. J. Eur. Ceram. Soc., 32 (2012) 2843–2852. https://doi.org/10.1016/j.jeurceramsoc.2012.01.020.
29. Forteza R., Far M., Seguí C., Cerdá V. – Characterization of bottom ash in municipal solid waste incinerators for its use in road base. Waste Manag., 24 (2004) 899–909. https://doi.org/10.1016/j.wasman.2004.07.004.
30. Kicińska A., Caba G. – Leaching of chlorides, sulphates, and phosphates from ashes formed as a result of burning conventional fuels, alternative fuels, and municipal waste in household furnaces. Energies, 14 (2021) 3936. https://doi.org/10.3390/en14133936.
31. Alam Q., Lazaro A., Schollbach K., Brouwers H. J. H. – Chemical speciation, distribution and leaching behavior of chlorides from municipal solid waste incineration bottom ash. Chemosphere, 241 (2020) 124985. https://doi.org/10.1016/j.chemosphere.2019.124985.
32. Ebert B. A. R., Kirkelund G. M. – Effects of chlorides and sulphates on heavy metal leaching from mortar with raw and electrodialytically treated MSWI fly ash. Waste Biomass Valorization, 13 (2022) 2673–2688. https://doi.org/10.1007/s12649-022-01686-0.

UNCORRECTED PROOF