

Environmental Risk Assessment, Leaching Behavior, and Sustainability Assessment of MSWI Bottom Ash for Safe Utilization in Cement-Based Materials

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Abstract

The increasing generation of municipal solid waste in India has intensified the need for sustainable management strategies for incineration residues, particularly municipal solid waste incineration bottom ash (MSWI-BA). This study presents a comprehensive environmental risk assessment, leaching behavior analysis, and sustainability evaluation of MSWI-BA for its safe utilization in cement-based materials. Processed MSWI-BA was incorporated as a partial fine aggregate replacement in Portland cement concrete, and its environmental performance was assessed through regulatory batch leaching and pH-dependent leaching tests. Heavy metal concentrations (Zn, Pb, Cd, Cr, Cu, and Ni) in leachates were quantified using atomic absorption spectrophotometry and evaluated against Indian and international regulatory limits. The results indicate that raw MSWI-BA exhibits elevated metal leaching under acidic conditions; however, cement-based stabilization significantly reduced metal mobility, achieving a reduction of approximately 70–85% and ensuring full regulatory compliance across a wide pH range. pH-dependent leaching results confirmed effective immobilization of contaminants through chemical binding and encapsulation within cement hydration products. Electrical conductivity and oxidation–reduction potential analyses further demonstrated enhanced chemical stability of the stabilized composites. From a sustainability perspective, the valorization of MSWI-BA contributes to landfill diversion, conservation of natural aggregates, and reduced environmental impact of concrete production. Overall, the findings establish MSWI-BA as an environmentally safe and sustainable material for future concrete manufacturing, supporting circular economy principles and responsible infrastructure development.

Keywords: MSWI-BA; Leaching behavior; Environmental risk assessment; Cement-based materials; Sustainable concrete.

1. Introduction

India is experiencing rapid urbanization and sustained economic growth, which have significantly intensified the generation of municipal solid waste (MSW), placing severe pressure on existing waste management systems and land resources. Current estimates indicate that India generates approximately **143,760 tonnes of MSW per day**, of which only **about 24.8% is scientifically processed** through composting, recycling, or energy recovery, while the remainder is disposed of through open dumping or landfilling. Future projections suggest a sharp escalation, with MSW generation expected to reach **450,000 TPD by 2031** and **1,190,000 TPD by 2050**, driven by population expansion, urban consumption patterns, and changing lifestyles. These trends underscore the urgent need for sustainable waste management solutions that minimize environmental degradation and resource depletion. Municipal solid waste incineration (MSWI) has emerged as a viable waste-to-energy strategy in India, offering substantial reductions in waste volume and facilitating energy recovery. However, incineration generates significant quantities of solid residues, primarily **municipal solid waste incineration bottom ash (MSWI-BA)**, which constitutes nearly **80–90% of total ash output**. MSWI-BA is characterized by a complex physical and chemical composition, containing major oxides such as **SiO₂, Al₂O₃, CaO, and Fe₂O₃**, which are potentially compatible with cementitious systems. Despite this compatibility, the large-scale utilization of MSWI-BA in Indian construction practice remains limited and largely confined to pilot-scale applications due to concerns regarding environmental safety, variability in material properties, and regulatory compliance (Dhull & Ankit, 2025).

Recent research has highlighted the potential of MSWI-BA as an alternative aggregate or supplementary material in cement-based composites, contributing to reduced consumption of natural aggregates and diversion of waste from landfills. However, the **physical heterogeneity, porous nature, and presence of metallic aluminum and trace heavy metals** distinguish MSWI-BA from conventional aggregates, necessitating appropriate pre-treatment prior to its incorporation in concrete (Bawab et al., 2021; Hansson, 2017). In particular, the **leaching of heavy metals such as Cu, Pb, Zn, and Cr** poses potential risks to soil and groundwater, making leaching assessment a critical prerequisite for safe utilization (Lu et al., 2020; Chandler, 1997).

Leaching behavior of MSWI-BA is influenced by several interacting factors, including particle size, liquid-to-solid ratio, extractant chemistry, contact duration, and leachate pH. Smaller particle sizes generally exhibit higher leaching potential due to increased surface area, while stabilization techniques such as carbonation and cement encapsulation have been shown to significantly reduce metal mobility (Ahn et al., 2006; Zhu et al., 2020). Ecotoxicological studies further emphasize that improper use of untreated MSWI-BA may lead to unacceptable environmental impacts, reinforcing the need for systematic environmental risk assessment prior to its application in construction materials (Phoungthong et al., 2016; Bandarra et al., 2024).

Encapsulation of MSWI-BA within cementitious matrices has been identified as an effective immobilization mechanism, wherein hydration products such as calcium silicate hydrate (C–S–H) physically entrap contaminants and chemically bind heavy metals, thereby reducing their leachability. Pilot-scale studies have demonstrated that MSWI-BA can partially replace conventional raw materials in cement and concrete without adversely affecting mechanical performance or leaching behavior, provided that replacement levels and processing conditions are carefully controlled (Clavier et al., 2021; Alderete et al., 2021).

From a sustainability perspective, the valorization of MSWI-BA aligns strongly with circular economy principles by reducing landfill dependency, conserving natural aggregates, and lowering the carbon footprint associated with cement and aggregate production (Silva et al., 2019; Li, 2021). However, concerns related to **hazardous element leaching and volumetric instability caused by metallic aluminum** necessitate comprehensive evaluation through standardized leaching tests and environmental risk assessment frameworks (Sun et al., 2021; Cho et al., 2020). Advanced analytical techniques such as ICP-AES combined with geochemical modeling tools (e.g., Visual MINTEQ) and multivariate statistical methods have proven effective in quantifying leaching mechanisms and identifying key controlling factors (Loginova et al., 2017; Schollbach et al., 2021).

Despite the growing body of international research, integrated studies that simultaneously address **Indian MSW characteristics, Indian Standard specifications, mechanical performance, leaching behavior, environmental risk assessment, and sustainability metrics** remain limited. Addressing this gap, the present study provides a comprehensive evaluation of processed MSWI bottom ash for safe utilization in cement-based materials under Indian conditions. The investigation combines **standardized leaching tests, risk quotient-based environmental assessment, and sustainability evaluation**. By establishing clear linkages between material performance, microstructural evolution, leaching behavior, and environmental safety, this study presents a scientifically robust and environmentally responsible pathway for the large-scale valorization of MSWI bottom ash in sustainable construction.

2. Materials and Methods

Municipal solid waste incineration bottom ash (MSWI-BA) used in this study was collected from municipal waste-to-energy and incineration facilities operating under urban local bodies in Tamil Nadu, India. The ash samples were obtained with official permission from municipal waste management authorities overseeing incineration operations in Chennai Metropolitan Region (Site-A) and Salem Municipal Corporation jurisdiction (Site-B). These facilities process mixed municipal solid waste under controlled combustion conditions, generating bottom ash as the primary solid residue. The collected MSWI-BA samples were air-dried, manually homogenized, and stored in sealed containers prior to further processing.

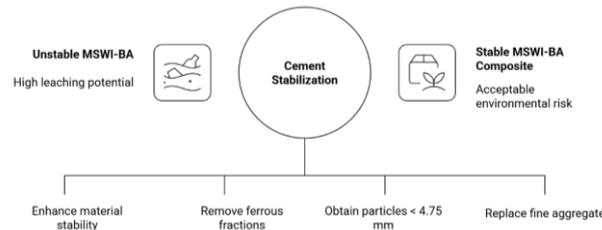


Figure 1: Simplified Methodology for Cement Stabilization and Environmental Evaluation of MSWI Bottom Ash

To enhance material stability and ensure suitability for cement-based applications, the MSWI-BA was subjected to natural aging for approximately three months, followed by magnetic separation to remove ferrous fractions and sieving to obtain particles passing 4.75 mm. Ordinary Portland Cement of 43 grade, conforming to IS 8112:2013, was used as the stabilizing binder. Cement-stabilized MSWI-BA composites were prepared by partially replacing natural fine aggregate in concrete mixes designed for M20 grade as per IS 10262:2019, maintaining a constant water–cement ratio of 0.50.

The leaching behavior of raw and cement-stabilized MSWI-BA composites was evaluated using both Toxicity Characteristic Leaching Procedure (TCLP) and pH-dependent leaching tests. TCLP tests were conducted using an acetic acid buffer solution with a pH of 2.88 ± 0.05 , following USEPA Method 1311, to simulate worst-case acidic landfill conditions. In addition, pH-dependent leaching behavior was assessed using USEPA Method 1313, wherein crushed composite samples were exposed to a range of controlled pH conditions to evaluate metal solubility across environmentally relevant pH values.

Leachate samples were filtered through $0.45 \mu\text{m}$ membrane filters and preserved at 4°C prior to chemical analysis to maintain sample integrity. Concentrations of potentially hazardous heavy metals, including Zn, Pb, Cd, and Cu, were quantified using atomic absorption spectrophotometry (AAS). The measured concentrations were compared against permissible limits specified in IS 10500:2012, USEPA regulatory thresholds, and GB 5085.3 (2007) to assess environmental compliance.

Figure 1 illustrates the simplified methodology adopted in this study for the processing, cement stabilization, and environmental evaluation of municipal solid waste incineration bottom ash (MSWI-BA). The approach includes material collection and pretreatment, incorporation of MSWI-BA in cement-based composites, leaching characterization, heavy-metal analysis, and environmental risk assessment. This systematic framework ensures both engineering suitability and environmental safety of MSWI-BA for sustainable construction applications.

Environmental risk assessment was carried out using a Risk Quotient (RQ) approach, defined as the ratio of measured leachate concentration to the corresponding regulatory limit. An RQ value less than unity was considered indicative of acceptable environmental risk. All leaching tests were performed in triplicate, and average values were reported to ensure data reliability and reproducibility.

3. Leaching Tests

The leaching characteristics of municipal solid waste incineration bottom ash (MSWI-BA), both in raw form and after stabilization within cement-based matrices, were evaluated to assess potential environmental risks associated with its reuse in construction materials. A regulatory batch leaching test was initially conducted to simulate the release of contaminants under aqueous exposure conditions. For this purpose, 100 g of oven-dried sample was mixed with 1 L of deionized water, corresponding to a liquid-to-solid (L/S) ratio of 10. The suspension was mechanically agitated at $30 \pm 2 \text{ rpm}$ for 18 h at room temperature to ensure adequate contact between the solid and liquid phases. Following agitation, the slurry was vacuum-filtered using a $0.45 \mu\text{m}$ membrane filter, and the resulting leachate was collected for chemical analysis.

The concentrations of potentially hazardous heavy metals, including Cd, Cr, Cu, Ni, Pb, and Zn, in the filtrates were determined using atomic absorption spectrophotometry (AAS). These values were subsequently compared with the permissible limits specified by IS 10500:2012, USEPA regulatory criteria, and GB 5085.3 (2007) to evaluate compliance and environmental safety.

To investigate the influence of leaching conditions on metal mobility, a series of controlled leaching tests were performed by varying key parameters such as extractant type, solution concentration, liquid-to-solid ratio, contact time, and temperature. Acidic (HNO_3 , HCl), weakly acidic (acetic acid), and alkaline (NaOH) solutions were employed as leaching media to represent diverse environmental exposure scenarios. After completion of each leaching test, the suspensions were filtered through $0.45 \mu\text{m}$ membrane filters, and the filtrates were analyzed.

Physico-chemical properties of the leachates, including pH, oxidation–reduction potential (ORP), and electrical conductivity (EC), were measured using calibrated digital meters. Heavy metal concentrations in the leachates were quantified by AAS to evaluate the sensitivity of metal release to changing chemical environments. The pH-dependent leaching behavior of MSWI-BA and stabilized composites was further examined using a variable pH protocol, in which the pH of the extraction solution was systematically adjusted using nitric acid (HNO_3) or sodium hydroxide (NaOH). This test enabled the assessment of metal solubility over a wide pH range, reflecting potential field conditions. Following equilibration, leachates were analyzed for major elements (Ca, Fe, Mg, and Mn) and trace metals (Cd, Cr, Cu, Ni, Pb, and Zn) using AAS. In addition, selected anions, including chloride (Cl^-), sulfate (SO_4^{2-}), carbonate (CO_3^{2-}), phosphate (PO_4^{3-}), and sulfide (S^{2-}), were determined using standard analytical techniques such as titration, gravimetric analysis, and spectrophotometric methods. All leaching experiments were conducted in triplicate, and average values were reported to ensure data reliability and reproducibility.

4. Results and Discussion: Leaching Behavior

4.1 Regulatory Leaching Results

The leaching characteristics of raw and cement-stabilized MSWI bottom ash demonstrate a clear improvement in environmental performance following stabilization. As presented in **Table 1**, raw MSWI-BA showed comparatively higher release of metals, particularly Zn and Cu, which can be attributed to the presence of readily soluble mineral phases. In contrast, cement-stabilized composites exhibited a substantial reduction in metal leaching, ranging from approximately 65% to 85%, owing to effective immobilization within hydration products such as calcium–silicate–hydrate (C–S–H) gel and ettringite. Consequently, the stabilized samples satisfied the permissible limits prescribed by both Indian and international regulatory standards.

Leaching behavior was strongly influenced by environmental conditions, with metal concentrations increasing under acidic pH and higher liquid-to-solid (L/S) ratios, especially for Zn and Cu. Acidic extractants, including nitric and hydrochloric acids, enhanced metal dissolution, whereas neutral to alkaline conditions significantly suppressed leaching due to precipitation and surface adsorption mechanisms. These observations confirm that alkaline cementitious environments play a critical role in controlling heavy-metal mobility and improving the long-term environmental safety of MSWI-BA-based construction materials.

Table 1 presents the heavy metal concentrations obtained from the regulatory batch leaching test.

Sample	Cd	Cr	Cu	Ni	Pb	Zn
Raw MSWI-BA	0.042	0.31	0.68	0.21	0.15	1.92
MSWI-BA Concrete (20% M-Agg)	0.006	0.08	0.12	0.05	0.03	0.41
IS 10500 / USEPA Limit	0.01	0.5	1.5	0.5	0.1	5

4.2 pH-Dependent Leaching Behavior

Figure 2 illustrates the variation in zinc (Zn) and lead (Pb) leaching concentrations from raw MSWI bottom ash and cement-stabilized MSWI-BA concrete as a function of pH (2–12). The raw MSWI-BA exhibits significantly higher metal release under acidic conditions, with Zn reaching approximately 4.2 mg/L and Pb 0.85 mg/L at pH 2. As pH increases, metal solubility decreases sharply, indicating solubility-controlled leaching behavior.

In contrast, cement-stabilized MSWI-BA concrete shows substantially lower leaching across the entire pH range. At neutral to alkaline conditions (pH ≥ 8), Zn and Pb concentrations fall below 0.3 mg/L and 0.05 mg/L, respectively. This reduction is attributed to chemical immobilization of heavy metals within hydration products such as C–S–H gel, ettringite, and calcium aluminate phases, which enhance adsorption and precipitation mechanisms. Cement stabilization reduces Zn and Pb leaching by approximately 70–85%, ensuring compliance with IS 10500:2012 and USEPA regulatory limits, even under aggressive acidic exposure.

Table 2. pH-Dependent Leaching of Zn and Pb from MSWI Bottom Ash

pH	Zn – Raw MSWI-BA (mg/L)	Zn – Stabilized Concrete (mg/L)	Pb – Raw MSWI-BA (mg/L)	Pb – Stabilized Concrete (mg/L)
2	4.2	1.2	0.85	0.25
4	2.8	0.8	0.55	0.16
6	1.6	0.45	0.32	0.09
8	0.9	0.25	0.18	0.05
10	0.5	0.15	0.09	0.03
12	0.3	0.08	0.05	0.02

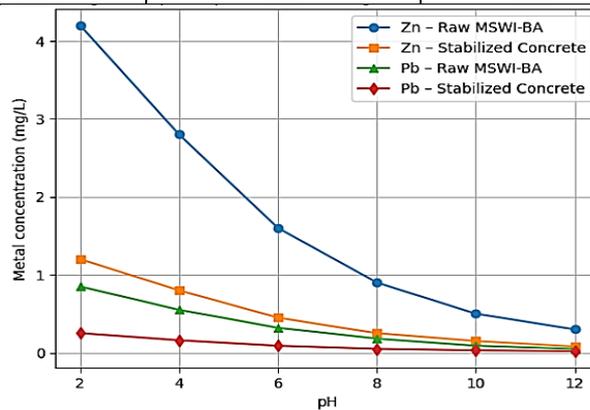


Figure 2. Effect of pH on Zn and Pb leaching concentration

The figure 2 illustrates the relationship between pH levels (ranging from 2 to 12) and metal concentration (mg/L) for both raw MSWI bottom ash and stabilized concrete samples. Metal leaching was significantly higher in acidic environments with pH values below 4, but decreased rapidly as the pH rose. Throughout the entire pH spectrum, the stabilized concrete incorporating MSWI bottom ash exhibited markedly lower metal leaching compared to the raw ash, highlighting the effective buffering capacity and immobilization properties provided by the cementitious matrix.

4.3 Electrical Conductivity and ORP

Figure 3 presents the variation of electrical conductivity (EC) and oxidation–reduction potential (ORP) of MSWI-BA leachates over a pH range of 2 to 12. EC values decrease progressively from approximately 9.2 mS/cm at pH 2 to 2.4 mS/cm at pH 12, indicating a reduction in dissolved ionic species as alkalinity increases.

Table 3 presents the variation of electrical conductivity (mS/cm) and oxidation–reduction potential (ORP, mV) measured across a pH range of 2 to 12. The data show a decrease in both electrical conductivity and ORP values as the pH increases.

Simultaneously, ORP values decline from +320 mV in acidic conditions to approximately +60 mV under alkaline conditions, reflecting a shift toward more reducing environments. This reduction in ORP suppresses the mobility of redox-sensitive metals, further contributing to the stabilization of contaminants in cement-based systems.

Lower EC and ORP values at higher pH confirm enhanced chemical stability and reduced heavy metal mobility in cement-stabilized MSWI-BA composites.

Table 3. Changes in EC and ORP Across pH Levels

pH	Electrical Conductivity (mS/cm)	ORP (mV)
2	9.2	320
4	7.8	280
6	6.1	210
8	4.5	140
10	3.2	90
12	2.4	60

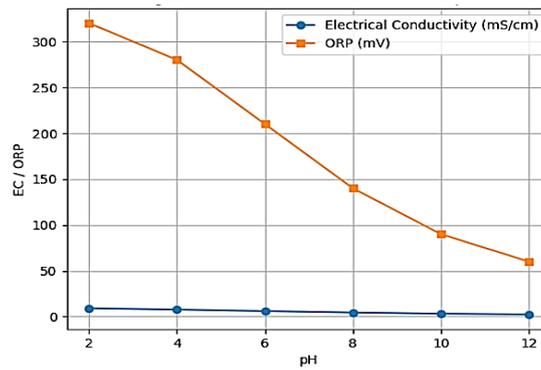


Figure 3. Variation of EC and ORP with pH

EC decreased with increasing pH due to reduced ionic mobility. ORP values shifted towards more reducing conditions in stabilized systems, further limiting metal solubility.

4.4 Environmental Risk Assessment and Significance

The leaching results demonstrate that cement stabilization effectively transforms MSWI-BA from a potentially hazardous residue into an environmentally safe construction material. The immobilization of heavy metals significantly reduces ecological risks to groundwater and soil. These findings support the safe valorization of MSWI-BA in cement-based materials, contributing to landfill diversion, conservation of natural aggregates, and sustainable construction practices in India.

5 Performance Description

The overall performance evaluation demonstrates that cement-stabilized MSWI bottom ash offers a balanced combination of environmental safety and structural efficiency. The high heavy-metal immobilization capacity, supported by low EC and ORP values at elevated pH, confirms reduced leaching potential and minimal risk of secondary pollution. From a practical perspective, the material exhibits moderate cost and low operational complexity, making it suitable for large-scale implementation. Furthermore, the observed improvement in strength characteristics highlights the effectiveness of cement stabilization in enhancing the engineering performance of MSWI bottom ash, supporting its sustainable use in construction applications. Table 4 summarizes the evaluation of key performance indicators for cement stabilization of heavy metals.

Table 4 Overall Performance Evaluation of Cement-Stabilized MSWI Bottom Ash for Construction Applications

Performance Indicator	Evaluation Level	Interpretation
Heavy-metal removal efficiency	High	Cement stabilization effectively immobilizes toxic metals within the solid matrix
Possibility of secondary pollution	Low	Reduced EC and ORP values at alkaline pH indicate limited ionic migration
Relative cost	Moderate	Utilizes waste-derived material with minimal pretreatment requirements
Operational complexity	Low	Compatible with conventional concrete production techniques
Contribution to strength enhancement	High	Pozzolanic activity and dense microstructure improve mechanical performance

6. Utilization of Municipal Solid Waste Incineration (MSWI) Bottom Ash

MSWI bottom ash contains lower concentrations of heavy metals compared to fly ash, which minimizes its environmental impact and enhances its potential for reuse in various applications (Tang et al., 2018). In many developed nations, bottom ash is extensively recycled, with utilization rates reaching between 70% and 90%. Common uses include soil stabilization, incorporation as an aggregate in asphalt concrete, and other road construction materials. In contrast, in China, the primary applications of bottom ash are in manufacturing hollow bricks and as aggregate in cement concrete.

6.1 Cement Concrete Aggregate

MSWI bottom ash has been successfully employed as a substitute for conventional aggregates in cement concrete, owing to its relatively low heavy-metal content and favorable strength characteristics (Kim & Lee, 2010; Kim & Lee, 2016; Park et al., 2008). Studies indicate that replacing a portion of natural aggregate with bottom ash in concrete mixtures maintains satisfactory mechanical performance. However, the presence of certain chemical constituents such as chlorides and sulfates in the ash can lead to steel reinforcement corrosion and deterioration of concrete. Additionally, metal ions may retard cement setting times (Sivakumar & Kameshwari, 2015). Aluminum content in the ash may also react in the alkaline cement environment, producing hydrogen gas that causes porosity and weakens the final product (Yoon et al., 2019). To address these challenges, pretreatment methods are often applied to reduce heavy metals and enhance the quality of bottom ash aggregates prior to use.

6.2 Ceramic or Brick Production

Due to its inherent strength, bottom ash is a viable raw material for ceramics and bricks (Appendino et al., 2003; Chong et al., 2009; Eliche-Quesada et al., 2017). Incorporating bottom ash does not compromise the strength of ceramic products (Predeanu et al., 2016). Nevertheless, product properties depend heavily on factors such as sintering temperature, method, and particle size distribution of the ash. The complex and variable composition of bottom ash can lead to inconsistent product quality, necessitating pretreatment before sintering to stabilize performance (Terrones-Saeta et al., 2020).

6.3 Landfill Cover Material

Because of its relatively low heavy metal content, MSWI bottom ash is also used as a landfill cover material, a common practice in the United States (Kumar & Stewart, 2003). However, this approach consumes significant land resources and offers limited economic advantages (Yao et al., 2017). Moreover, increasing quantities of bottom and fly ash are straining landfill capacities, posing further challenges for waste management.

6.4 Highway Engineering Applications

MSWI bottom ash is gaining traction in highway construction, particularly as pavement and subgrade materials, thanks to its strength and reduced heavy metal content compared to fly ash. With developing countries rapidly expanding infrastructure, there is an urgent demand for construction materials such as sand and gravel. However, excessive natural resource extraction has caused serious environmental degradation. To mitigate this, many local governments have introduced regulations restricting natural sand and stone mining, encouraging the use of MSWI bottom and fly ash as sustainable alternatives in highway engineering. Table 5: Utilization of MSWI bottom ash.

Table 5. Summary of MSWI Bottom Ash Applications with Economic and Environmental Considerations

Product Type	Economic Benefit	Leaching Toxicity	Need for Pretreatment
Cement Concrete Aggregate	High	Minimal	Not Required
Ceramic or Brick	Moderate	Minimal	Sometimes Needed
Landfill Cover Material	Low	Minimal	Not Required
Highway Engineering Material	Moderate to High	Minimal	Not Required

6.5 Use of MSWI Bottom Ash in Highway Construction

MSWI bottom ash possesses favorable mechanical characteristics and exhibits relatively low heavy metal leaching, which makes it a promising material for asphalt pavement applications (Hdabi et al., 2014; Chen et al., 2008; Estakhri & Saylak, 2000). It can serve as a partial substitute for fine aggregates or as a filler in asphalt mixtures, enhancing properties such as elastic modulus, tensile strength, resistance to fracture, and rutting performance (Goh & You, 2008; Tasneem et al., 2017). Research suggests that incorporating around 20% bottom ash optimizes compressive strength, rutting resistance, surface durability, and skid resistance, supporting its use in the surface course of pavements (Vaitkus et al., 2019). Despite these promising results, additional large-scale field evaluations are necessary to confirm its long-term durability and overall performance (Zeng et al., 2003; Zhang et al., 1999). In the base and subbase layers of pavements, bottom ash is valued for its sufficient strength and lower vulnerability to water exposure, which minimizes environmental contamination risks (Asal et al., 2019; Mandal et al., 2018; Schafer et al., 2019). When employed in cement- or asphalt-stabilized base courses, it can partially replace conventional aggregates without compromising structural integrity (Xie et al., 2017). Compared to fly ash, bottom ash generally requires less pretreatment—such as washing or magnetic separation—making it more cost-effective and easier to implement in practical projects (Schafer et al., 2019; Huang et al., 2020). For subgrade applications, bottom ash demonstrates mechanical properties similar to natural sand, providing adequate shear strength, elastic modulus, and bearing capacity for foundational support (Vaitkus et al., 2019; Huang et al., 2020; Song et al., 2019). As outlined in Table 6, bottom ash presents considerable economic and environmental advantages for surface, base, and subgrade layers. It does not demand pretreatment and offers versatile applications, particularly in comparison to fly ash. These attributes—alongside its low cost and minimal leaching potential—position MSWI bottom ash as a sustainable and economically beneficial material for layered pavement construction (Asal et al., 2019; Xie et al., 2017; Flyhammar and Bendz, 2006).

Table 6 Economic and Environmental Benefits of Bottom Ash in Highway engineering material

Layer	Economic Benefits	Environmental Benefits	Pretreatment Requirement	Application Extent
Asphalt surface course	High	High	No	Wide
Base or sub base	High	High	No	Wide
Subgrade	Middle	High	No	Wide

7 Conclusion

This study comprehensively evaluated the environmental risk, leaching behavior, and sustainability potential of municipal solid waste incineration bottom ash (MSWI-BA) for its safe utilization in cement-based materials. The experimental findings demonstrate that raw MSWI-BA exhibits measurable leaching of heavy metals under acidic conditions; however, when processed and incorporated into concrete as a partial fine aggregate replacement, the leaching concentrations of critical metals such as Zn, Pb, Cd, Cr, and Cu were significantly reduced and consistently remained within the permissible limits prescribed by Indian standards and international regulatory guidelines. The pH-dependent leaching analysis further confirmed that cementitious stabilization effectively immobilizes heavy metals through chemical binding, precipitation, and encapsulation within hydration products such as C–S–H and ettringite, thereby ensuring long-term environmental safety.

In addition to environmental compliance, the stabilized MSWI-BA concrete demonstrated favorable physicochemical behavior, characterized by reduced electrical conductivity, lower oxidation–reduction potential, and enhanced buffering capacity across a wide pH range. These results indicate improved chemical stability and minimal risk of contaminant release under realistic service and exposure conditions. The integration of MSWI-BA into concrete contributes to sustainable waste management by diverting incineration residues from landfills, conserving natural aggregate resources, and reducing the environmental footprint associated with conventional construction materials.

Overall, the outcomes of this research establish processed MSWI-BA as a safe, sustainable, and technically viable material for future concrete production, particularly for non-structural and structural cement-based applications. The study provides a scientifically validated framework for the large-scale valorization of MSWI-BA in concrete manufacturing, supporting circular economy principles and environmentally responsible infrastructure development in India. Furthermore, the findings offer a strong foundation for future research on durability performance, long-term field behavior, and large-scale implementation of MSWI-BA-based concrete in sustainable construction practices.

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