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Circular and Sustainable Approaches for the Management and Treatment of Incineration Bottom Ash

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Hazardous wastes containing heavy metals, such as incineration bottom ash (IBA) from industrial waste incinerators, typically require stabilization with costly chemical reagents prior to disposal in non-hazardous waste landfills. This study explores a more sustainable and circular treatment strategy aimed at rendering IBA suitable for disposal in landfills designated for stable, non-reactive waste. The proposed process involves an initial extraction step using sodium hydroxide (NaOH) at varying concentrations (0.5 M, 1 M, and 2 M), followed by a washing phase. Uniquely, landfill leachate—a waste by-product itself—was employed both as a diluent in the extraction solution and as a washing agent, thereby minimizing the use of freshwater resources. Experimental results confirmed the effectiveness of the treatment in meeting regulatory limits, paving the way for the development of circular and sustainable approaches for the management of hazardous industrial waste.

* 1. Introduction

The demand for the safe disposal of multisource solid waste, such as municipal sludge, medical waste, and industrial residues, is increasing (Zhang et al., 2025). Waste-to-energy technologies offer the advantages of reducing the volume of waste to be landfilled and recovering energy. Among them, waste incineration recorded a global capacity of 1.70 million tons per day in 2022 (Xie et al., 2023). However, incineration generates three primary residues: bottom ash, fly ash, and air pollution residues. Incineration bottom ash (IBA) is of particular concern due to its content of heavy metals and other hazardous pollutants (Phua et al., 2019).

IBA is a highly heterogeneous material with a highly variable composition, depending on the incinerated waste, and contains particles ranging from micrometers to several centimeters. The characteristics of IBA can also be affected by the operating conditions of waste incineration, such as the type of combustion (Šyc et al., 2024). Chemical speciation of heavy metals is critical for assessing IBA’s hazardous properties and determining its appropriate classification (Hennebert et al., 2014). Although municipal solid waste IBA is commonly landfilled, treatment is often required to stabilize contaminants and enable its disposal in non-hazardous waste landfills. This treatment aims to reduce the long-term leaching potential of toxic elements such as heavy metals and persistent organic compounds.

Stabilization becomes particularly challenging due to the distinct leaching behaviours of different metals. For example, while many metals exhibit lower solubility under alkaline conditions (Baba et al., 2010; Izquierdo and Querol, 2012; Oreščanin et al., 2007), molybdenum (Mo) forms highly soluble molybdate ions ($MoO\_{4}^{2-}$), which remain mobile even at high pH (Xu et al., 2013). As a result, conventional alkaline stabilization methods may be insufficient for Mo-rich residues, complicating treatment strategies and increasing costs (Mancini et al., 2022).

Mancini et al. (2022) proposed to immobilize molybdate ions with a ferrous sulfate‑based additive using the reducing properties of the Fe2+ ion, in compliance with specific pH and redox potential conditions, which were crucial for the partial stabilization and immobilization of Mo. They also investigated the use of other wastes (i.e., spent fluid catalytic cracking catalyst) as alternative reagents in Mo-contaminated hazardous waste enhanced stabilization. In recent years, novel techniques have been developed for the recovery of valuable metals, though economic viability is not always met. Studies on the recovery of heavy metals have focused on chemical extraction using inorganic or organic leaching agents (Ko et al., 2005; Lv et al., 2023; Tampouris et al., 2001; Wang et al., 2023) or chelating agents (Begum et al., 2012; Lim et al., 2005). In some studies, EDTA has been used for the removal of heavy metals from contaminated soils (Luciano et al., 2013, 2012). Depending on the target metal, acid (Race et al., 2016; Wang et al., 2023; Zhai et al., 2018), or alkaline solutions (Wang et al., 2021) are used.

In this study, a sustainable treatment of IBA, classified as hazardous waste, has been developed and tested (as (a) a direct treatment to render IBA compatible with the limits of admissibility in landfills for non-hazardous waste, or at least (b) a pre-treatment step before a stabilization process. The key aspect and the novelty of the proposed process is the use of a waste-derived liquid (landfill leachate) as a diluent and washing solution. This leads to greater efficiency and circularity in the use of resources and the possibility of implementing industrial symbiosis exchanges among companies.

* 1. Materials and methods

The incineration bottom ash (IBA) used in this study was obtained from an industrial waste incineration plant. The samples appeared grey to dark grey in color and exhibited high heterogeneity, reflecting the complexity of the incinerated feedstock. Table 1 presents the elemental composition of the analyzed IBA and compares it with values reported for IBA from automotive shredder residue (ASR) (Mancini et al., 2014) and municipal solid waste incinerators (Šyc et al., 2020).

Due to limited literature on IBA from special industrial wastes, most comparative data are derived from municipal solid waste studies. Nevertheless, metals such as Zn, Cr, and Cd were found at similar concentrations to those in ASR, as shown in Table 1. In contrast, the tested IBA exhibited lower Pb but higher Se content compared to typical municipal waste-derived ash.

Table 1: Elemental composition of IBAs [ppm].

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | As | Ba | Cd | Cr | Cu | Hg | Mo | Ni | Pb | Sb | Se | Zn |
| This work | 12.79 | 55.55 | 5.76 | 182.23 | 1.36 | 0.85 | 125.68 | 294.80 | 0.27 | 107.58 | 14.85 | 3275.44 |
| Mancini et al. (2014) | 22.53 | - | 2.55 | 306.2 | 32.42 | <0.1 | - | 265.5 | 3824 | - | 3.78 | 14.73 |
| Šyc et al. (2020) | 0.12-190 | 69-5700 | 0.3-70 | 20-3400 | - | - | 2.5-280 | 7-4300 | 74-14000 | - | 0.05-10 | 10-20000 |

The proposed treatment was designated in three phases (Figure 1):

1. Extraction phase: IBA was contacted with an extracting alkaline solution (NaOH) at different concentrations (0.5 M, 1.0 M, and 2.0 M) prepared using landfill leachate as the solvent. The solid-to-liquid (S/L) ratio was maintained at 1:5, with 100 g of IBA mixed with 500 mL of solution. Samples were agitated in a rotary shaker for 2 hours.
2. Solid-liquid separation: The mixture was filtered under vacuum using a Büchner funnel, a conical flask, and a vacuum pump to separate the solid residue from the extraction liquid.
3. Washing phase: The recovered solid was washed using landfill leachate with an S/L ratio of 1:2. Three washing cycles were performed. Additionally, for 0.5 M NaOH extraction, the single-cycle washing was also evaluated.



Figure 1: Experimental design and stages of the treatment process.

Table 2 summarizes the key experimental conditions, including NaOH concentration, reagent-to-waste ratio, and number of washing cycles.

Table 2: Experimental conditions of the industrial waste IBA treatment process with NaOH-based extraction and landfill leachate solution-based washing.

|  |  |  |  |
| --- | --- | --- | --- |
| Experiment | NaOH concentration [M] | Reagent/waste [%] | Cycles |
| A1 | 0.5 | 10 | 1 |
| A2 | 0.5 | 10 | 3 |
| B | 1.0 | 20 | 3 |
| C | 2.0 | 40 | 3 |

The landfill leachate used as a solvent and washing agent was characterized prior to use. Table 3 reports the concentrations of the main components. The leachate exhibited a basic pH (10.8) and contained notable concentrations of chlorides and sulphates.

Table 3: Characteristics of the landfill leachate [mg/l].

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| As  | Ba | Cd | Cr | Cu | Hg | Mo | Ni | Pb | Sb | Se | Zn |
| 0.2  | 0.13 | 0.01 | 0.02 | 0 | 0.03 | 4.5 | 0.22 | 0.02 | 0.11 | 0.07 | 0.80 |
| Chlorides |  | Fluorides |  |  | Sulphate  |  | DOC |  | TDS |  |  |
| 47054.74 |  | 0 |  |  | 7870.047 |  | 225.165 |  | 85360 |  |  |

Leaching tests were performed, before and after the treatment, to determine the suitability of the treated IBA for disposal in landfills for stable non-reactive waste, in accordance with the limits defined by the Italian law (DM 27/09/2010). Dissolved organic carbon (DOC) in the leachate was measured using the Elementar Enviro TOC analyzer according to UNI EN ISO 16192:2012 and UNI EN 1484:99. Total dissolved solids (TDS) were determined by oven-drying 25 mL of 0.45 μm-filtered leachate at 105 °C (UNI EN ISO 16192:2012; UNI EN 15216:202). Metals and anions were determined using the ICP-MS (NexION 350x), following the UNI EN ISO 17294-2:2023 method.

Furthermore, metal concentrations in the solid matrix (before and after treatment) were determined through acid digestion in aqua regia followed by ICP-MS analysis to evaluate the reduction efficiency.

* 1. Results and discussion

The results of the treatment experiments using NaOH concentrations of 0.5 M, 1 M, and 2 M are summarized in Table 4 for the critical metals present at high concentration in the IBA. The pH remained stable around the initial value of 12.6 throughout the extraction process.

Table 4: Metal concentration [ppm] in the solid matrix of each sample.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| NaOH concentration [M] | Cr | Mo | Sb | Se | Zn |
| 0.5 | 161.22 | 90.51 | 83.32 | 12.03 | 3210.14 |
| 1.0 | 142.01 | 90.94 | 70.98 | 8.92 | 3025.98 |
| 2.0 | 126.78 | 53.18 | 107.58 | 9.62 | 2732.03 |

A comparison of Table 4 (post-treatment metal concentrations) with Table 1 (initial composition) reveals that metal removal efficiency varied according to both the type of metal and the concentration of the extracting agent. The maximum removal efficiencies obtained with 2 M NaOH solution were 58% and 40% for Mo and Se, respectively. These elements are of particular concern, as their concentrations in the leachate from untreated IBA exceeded the regulatory thresholds for landfilling non-hazardous waste, as shown in Table 5 (DM 27/09/2010), which reports the results of the leaching tests and the regulatory limits.

Table 5: Concentrations [mg/l] in the eluate from leaching tests and comparison with the threshold values for the acceptability in landfills for non-hazardous waste (DM 27/09/2010, Table 5A).

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | As  | Ba | Cd | Cr | Cu | Hg | Mo | Ni | Pb | Sb | Se | Zn |
| Untreated IBA | 0.002  | 0.359 | 0 | 0 | 0 | 0.006 | 2.21 | 0 | 0.011 | 0.004 | 0.124 | 0.147 |
| DM 27/09/2010 | 0.2 | 10 | 0.1 | 1 | 5 | 0.02  | 1 | 1 | 1 | 0.07 | 0.05 | 5 |
|  | Chlorides |  | Fluorides |  |  | Sulphate |  | DOC |  | TDS |  |  |
| Untreated IBA | 720.024 |  | 0.427 |  |  | 1472.07 |  | 16.6 |  | 4372 |  |  |
| DM 27/09/2010 | 1500 |  | 15 |  |  | 2000 |  | 80 |  | 6000 |  |  |

The Mo removal efficiency from the solid matrix achieved in this study (58%) was compared with results reported in the literature for other Mo-contaminated hazardous waste treatments, as summarized in Table 6.

Table 6: Mo removal efficiency (%).

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| This work | (Huang et al., 2019) | (Wang et al., 2021) | (Wang et al., 2018) | (Ye et al., 2019) |
| 58 | 94 | 88-96 | 94.3 | 99 |
| Alkaline leaching (NaOH) and landfill leachate at room temperature | Blank and sodium carbonate roasting and leaching with tap water | Roasting process and alkaline leaching (NaOH;T=70°C-120°C) | Ultrasonic leaching with sodium carbonate | Microwave roasting and ultrasound-assisted leaching with hot water with sodium carbonate |

Huang et al. (2019) employed a two-step roasting process—initial blank roasting to oxidize molybdenum sulfide, followed by sodium carbonate roasting—to produce soluble sodium molybdate, achieving a Mo extraction efficiency of 94% through subsequent water leaching. Wang et al. (2021) developed a two-stage method involving thermal roasting at 70–120 °C and alkaline leaching using NaOH (10–40 wt%), obtaining removal efficiencies between 88% and 96%. Other advanced technologies have also been explored for Mo recovery from spent catalysts, including ultrasonic-assisted leaching (Wang et al., 2018), microwave-assisted leaching (Ye et al., 2019), and mechanical activation (Li et al., 2017; Park et al., 2007). Despite their high efficiency, these methods often involve complex operating conditions, high energy consumption, and are rarely implemented at full industrial scale due to economic and technical constraints. In contrast, the method proposed in this study achieves substantial Mo reduction under ambient conditions, without requiring elevated temperatures or energy-intensive steps. Moreover, the process employs landfill leachate as the solvent, thereby reducing reliance on fresh water and aligning with circular economy principles. Importantly, while previous studies focused on Mo recovery due to its high content and economic value, the goal of this work is to minimize the leachability of Mo in IBA to meet regulatory thresholds for stable non-reactive landfill disposal, using cost-effective and resource-efficient techniques. Higher NaOH concentrations can lead to increased removal efficiency. However, selecting the optimal concentration requires balancing treatment performance with economic and environmental considerations, also in relation to the specific purposes of the treatment.

Treatment with NaOH concentration between 0.5 M and 1.0 M proved to be the most effective in simultaneously reducing the leachability of both Mo and Se below the regulatory limits for disposal in landfills for non-hazardous, stable, non-reactive waste. However, an elevated chloride concentration was observed in the eluate following treatment with the 0.5 M NaOH solution, likely due to the inherently high chloride content of the landfill leachate used (Table 2). To balance metal removal efficiency with chloride management, reducing the number of washing cycles may be a viable strategy. Preliminary tests revealed that a single washing cycle after 0.5 M NaOH extraction resulted in Mo concentrations below the legal threshold. However, Se concentrations remained above the limit. This indicates that additional optimization, particularly of the washing step, is needed to meet all regulatory requirements. Figure 2 illustrates the contrasting trends in Mo and Se leachability with increasing NaOH concentration, demonstrating a monotonic but inverse effect for the two elements.



Figure 2: Mo and Se concentration in the leaching tests.

Finally, Figure 3 compares the chemical characteristics of the extraction and washing liquids to those of the original landfill leachate. The similar magnitudes of contaminant concentrations suggest that the process does not significantly degrade the quality of the leachate, nor does it substantially increase disposal costs.



Figure 3: Comparison between extraction and washing liquid characteristics with the original landfill leachate.

* 1. Conclusions

Unlike most studies that rely on water or virgin resources as solvents, this research introduces a circular treatment approach for IBA using NaOH dissolved in landfill leachate. The method was tested on IBA originating from a special industrial waste incineration plant, with NaOH concentrations of 0.5 M, 1 M, and 2 M, and reagent-to-waste ratios ranging from 10% to 40%. The proposed process, comprising extraction, separation, and multi-cycle washing, successfully reduced the metal concentration in the solid matrix and the Mo and Se concentrations in the leachate, meeting the regulatory thresholds for disposal in stable, non-reactive landfills.

With 2 M NaOH, a reduction efficiency of Mo and Se of 58% and 40% respectively, was achieved. All treated samples complied with limits for TDS, fluorides, sulphates, and DOC. However, chloride levels exceeded regulatory limits in the 0.5 M NaOH treatment with three washing cycles. Mo concentrations met legal thresholds in all treated samples, while Se limits were only satisfied in treatments with 0.5 M and 1 M NaOH.

These findings suggest that a lower NaOH concentration (0.5–1 M) may be sufficient to meet environmental standards for Mo (though barely achieved) and Se while minimizing reagent use and operational costs. Additionally, the analysis of the extraction and washing liquids indicates that the IBA treatment process does not significantly deteriorate the quality of the landfill leachate, which would require disposal regardless. While further economic analysis is warranted, this study demonstrates the potential of a resource-efficient and circular method for treating hazardous IBA for compliant disposal in non-hazardous waste landfills.

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