



Evaluating the Concentration and Leachability of Heavy Metals in Electric Arc Furnace Dust: Implications for Environmental Management

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Abstract: With the expansion of steel production via electric arc furnaces, an increase in dust generation—a by-product of these operations—poses substantial challenges. These difficulties stem from land use restrictions for large-scale dust waste storage and the environmental implications of heavy metal contamination inherent in the dust. In an effort to promote the repurposing of this potentially hazardous solid waste, this study examines the concentration and leachability of various heavy metals in this dust. Digestion of the dust samples was carried out in a controlled laboratory setting, after which the concentrations of iron (Fe), magnesium (Mg), zinc (Zn), manganese (Mn), nickel (Ni), lead (Pb), cadmium (Cd), and cobalt (Co) were determined using flame atomic absorption spectrometry. The mean concentrations of these heavy metals in the dust were found to be in the following descending order (in mg/kg): Fe > Mg > Zn > Mn > Ni > Pb > Cu > Cd > Co. Water leaching tests were subsequently conducted, revealing that Co and Cd exhibited the greatest leachability at varying pH levels. Conversely, Fe and Ni displayed minimal leachability. These findings have significant implications for the reuse and environmental management of electric arc furnace dust.

Keywords: Electric Arc Furnace Dust (EAFD); Heavy metals; Leaching; pH; Environmental pollution

1 Introduction

Iron, comprising approximately 5% of the Earth's crust, is primarily extracted via the carbon reduction method [1, 2]. Among iron alloys, steel reigns prominent, produced through three principal methods: traditional high furnace, direct iron ore reduction, and via the melting of sponge iron and steel scrap using an electric arc furnace (EAF) [1, 2]. Since 1996, crude steel production has surged worldwide, with nearly 1.7 billion tons being generated in 2017, and 30% of this amount produced via the EAF method [3].

However, each ton of steel produced using EAFs concurrently generates approximately 15-30 kg of electric arc furnace dust (EAFD) [4]. This by-product is characterized by the presence of heavy metals such as Cd, Pb, Cu, Mg, Cr, and Fe, leading to its classification as hazardous waste under the European waste and EPA lists [4, 5]. A survey of the literature indicates that about 3.7 million tons of EAFD are produced annually as a steel industry byproduct worldwide [6]. Consequently, an understanding of the physical and chemical characteristics of EAFD is paramount for its processing, recycling, and safe disposal.

Sustainable development hinges on the efficient use, reuse, and recycling of resources. This approach reduces waste disposal, lowers greenhouse gas emissions, conserves raw materials, and optimizes energy and water management. Nevertheless, EAFD, due to its toxic composition, particle size, high volume and weight, and daily production rate, presents serious environmental issues when left exposed in open environments. It contributes to soil, ground-water, and air pollution [7, 8]. Therefore, the concentration of heavy metals in EAFD and the environmental issues related to its disposal necessitate investigations into its recycling and reuse. The recovery of iron concentrates and

zinc for use in steel or cast-iron production, or for commercial purposes, and the transformation of EAFD into non-hazardous waste are significant considerations in EAFD processing [9, 10].

The environmental fate of pollutants is often determined by the aqueous solubility, a fundamental molecular characteristic. The solubility of compounds, hydroxides, and salts with weak anions is directly influenced by pH. The pH of a washing solution can alter the quantity of pollutants released into the environment [11]. pH-dependent leaching tests, which are more practical and relevant than merely determining the total concentration, are commonly used to ascertain the environmental risks of waste materials and study the mobility of cations and anions [12].

Within the context of Esfarayen-Iran Steel factory, approximately 3,000 tons of dust are produced annually by EAFs. This dust is stored under inadequate conditions, exacerbating the risk of environmental harm as the dust is exposed to natural elements such as rain, potentially leading to the leaching of a substantial proportion of heavy metals. The present study aims to quantify the heavy metals in dust samples from this site and identify the most leachable toxic elements in response to water exposure.

2 Methodology

2.1 Study Area

The study was conducted within a geographical area demarcated by Latitude $40^{\circ}36'' - 17^{\circ}37'$ and Longitude $57^{\circ}56'' - 58^{\circ}7''$. Sampling of Electric Arc Furnace Dust (EAFD) at the Esfarayen Steel Factory was performed at three randomly selected locations, designated A, B, and C. At each location, five samples were collected and composited, yielding a total weight of 3 kg per location. Newly produced EAFD was categorized as sample A, slightly aged EAFD as sample B, and the oldest EAFD as sample C.

2.2 EAFD Analysis

Samples were subjected to laboratory analysis wherein they were initially dried in an oven for 24 hours at 110°C . A 5 g portion of each sample was subsequently digested using 50 ml of Aqua regia (comprising a 3:1 ratio of 33% HCl and 65% HNO_3) in a 100 ml Erlenmeyer flask [13]. To ensure complete digestion, samples were heated at 90°C for 90 minutes, followed by a heating period at 120°C . After cooling, the samples were filtered and diluted with distilled water in a 100 ml volumetric flask, then stored at 4°C until the determination stage. The concentrations of the metals under study were quantified using a flame atomic absorption spectrometer (FAAS - Perkin Elmer AAnalyst 240). Dust chloride content was measured via the argentometric titration method [14, 15].

To evaluate the quantity of metals leachable from the dust, 20 g samples were transferred to Erlenmeyer flasks, and 50 ml of distilled water with varying pH levels (1, 3, 5, 7, 11) was added, alongside diluted solutions of HCl, HNO_3 , and H_2SO_4 (1, 3M) [4].

The pH and electrical conductivity (EC) of the prepared samples in solution (comprising a 1:2.5 ratio of dust to distilled water) were measured using a multimeter [16].

3 Results and Discussion

3.1 Heavy Metal Concentration in EAFD Samples

Table 1 presents the concentration of heavy metals within Electric Arc Furnace Dust (EAFD) samples. Iron (Fe) concentrations are found to consistently exceed those of other elements in all dust samples. Comparisons with previous studies suggest that the zinc content in the current study is less than those reported in prior investigations, potentially attributable to the primary substance and furnace charging compounds [17–21]. High concentrations of chloride present in EAFD are noted to hinder the value of recycled zinc oxide due to the adverse effect of chlorine on zinc production, as well as its potential to release persistent environmental pollutants such as dioxin ($\text{C}_4\text{H}_2\text{O}_2$) [22]. Table 1 illustrates a high chlorine content that could impede the zinc extraction process, indicating that the commercial recovery of zinc from the investigated EAFD may not be economically feasible.

Table 1. The amount of heavy metal in the studied EAFD (mg/kg)

	Fe	Zn	Cu	Ni	Mn	Mg	Co	Pb	Cd	Cl	pH	EC*
A	376000	6840	408	9600	11360	44240	40.6	190	6.8	0.7	13.8	106.2
B	364000	5770	378	142	10620	3780	33/2	492	103.4	1.1	13.3	108.3
C	326000	29420	470	4.8	9500	28100	29/4	2980	46.8	0.7	9.9	24.2
Mean	355333	3993.3	418.8	3249	10493.3	25373.4	34.4	1220.6	52.3	0.8	12.4	79.6

Note: *mSiemens/cm

3.2 Complexity and Variation in EAFD Composition

The chemical composition of EAFD is revealed to be complex and varied, influenced by factors including the type of scrap used, the type of steel produced, working conditions, and the process types [23]. Minor alterations in the ratio of charged materials in a melting process can change the chemical composition of EAFD, therefore heavy metal amounts in different samples could reflect the source of raw materials. The fact that Fe comprises approximately 37.6% of EAFD's chemical composition suggests that it could be recovered as raw material from dust. The significant quantity of Fe in EAFD supports the potential for waste reuse in various applications, including concrete production and use as a magnetic adsorbent [20].

3.3 Impact of pH on Metal Accumulation and Mobility

pH levels significantly influence the accumulation and mobility of heavy metals in soil or solid waste. Metals are generally more cationic and are attracted by the negative adsorbent, while in alkaline soils, metals tend to sediment and demonstrate less mobility. Therefore, the risk associated with heavy metals in acidic samples is greater than in alkaline samples [24, 25]. High electrical conductivity also suggests the presence of cationic and absorbable metallic elements. As presented in Table 1, the physicochemical properties analysis of dust reveals higher pH values in newly deposited samples. Over time, dust samples stored at the depot center decrease in alkalinity and electrical conductivity. This supports the idea that dust storage in unroofed areas leads to the removal of alkali and metal ions from the samples [23].

3.4 Leaching Behavior of Heavy Metals

Prior studies have suggested that the ability to wash heavy metals from EAFD decreases as pH increases, however, the leaching of lead (Pb) and chromium (Cr) increases with pH increment [23]. Our results on heavy metal leaching deviate slightly from these previous studies. Heavy metals such as cadmium (Cd) and Pb are recognized as toxic, unnecessary for life, and persistent pollutants that cause harm across various levels of the food chain [26]. Figure 1 shows the leaching of dusts with water at different pH levels, with the highest amounts of leached zinc (Zn) and magnesium (Mg) observed at a pH of 7. An increase in alkalinity dramatically reduces the amount of Zn and Mg [20].

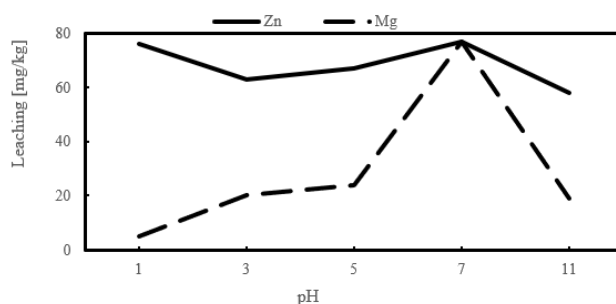


Figure 1. The amount of leaching Zn, Mg with different pH levels

Figure 2 illustrates the highest dissolution of Cd and Pb at a pH of 5. This suggests that during rainfall, the potential for leaching and the influence of Cd and Pb from dust to soil and groundwater is elevated. The amounts of cobalt (Co), copper (Cu), and nickel (Ni) remain roughly constant in acid and neutral environments and are less dependent on water pH, whereas Fe shows a significant rise in an alkaline environment. Manganese (Mn) tends to leach only at pH = 3, with no change in leaching observed with increasing pH [23].

Comparing the total amount of heavy metals with the amount of leached metals in Figure 3, it is found that Co and Cd metal ions demonstrate the highest leaching rates compared to other studied heavy metals. The leaching percentages of metals at pH = 5 were determined to be in the order Co > Cd > Zn > Pb > Cu > Mg > Fe, Ni, Mn. EAFD samples collected from an unroofed outdoor location at the Esfarayen Steel factory were directly exposed to rain and wind. Given the high concentrations of toxic metals such as Cd and Pb in these samples, there exists the potential for long-term soil and groundwater pollution caused by agents such as rainfall, displacement, and emission by wind [23, 26].

3.5 Effect of Acid Concentration on Metal Leaching

Figure 4 demonstrates that the percentage of Zn leaching increases with rising concentrations of hydrochloric acid (HCl) and sulfuric acid (H₂SO₄). However, changes in nitric acid (HNO₃) concentration from 1 to 3 M does not notably influence metal leaching. Both Pb and Ni exhibit the lowest reactivity and leaching levels in both

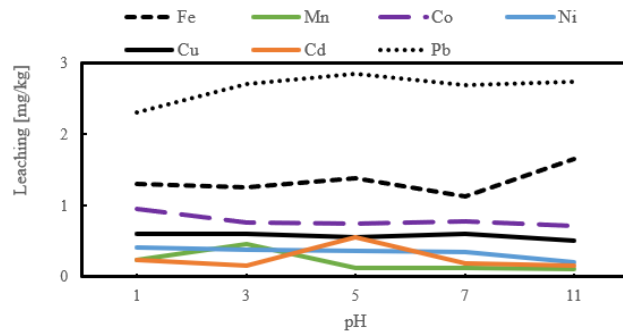


Figure 2. The amount of leaching Zn, Mg with different pH levels

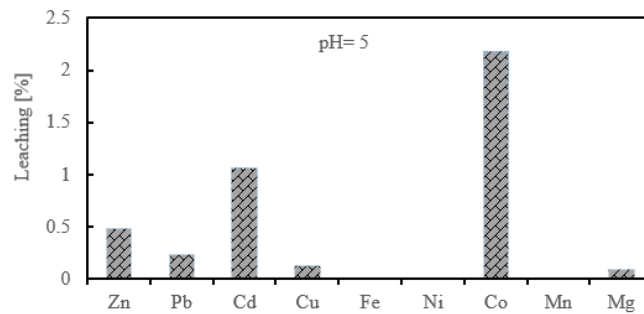


Figure 3. Effect of water pH value on the heavy metals leaching from EAFD

concentrations of the utilized acids. Conversely, the percentage of copper (Cu) leaching increases at a concentration of 3 molar H_2SO_4 . Less than 10% of iron (Fe) was found in both concentrations, and the percentage of Co and Mn increased with a shift in concentration from 1 molar to 3 molar acids [20, 23].

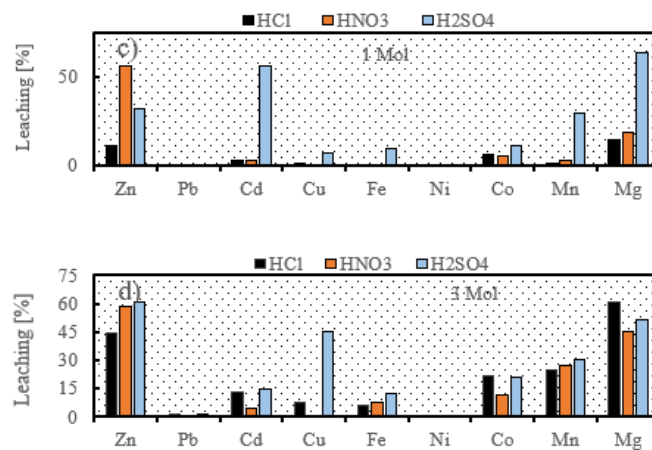


Figure 4. Effect of water pH value on the heavy metals leaching from EAFD

4 Conclusions

The findings of this study on Electric Arc Furnace Dust (EAFD) highlight the viability and cost-effectiveness of recovering iron concentrates from the waste material. However, the low quantity of zinc (Zn) in EAFD, coupled with the presence of chloride ions, renders its recovery economically unfeasible. The leaching behavior of metals at different pH levels indicates that Zn and magnesium (Mg) exhibit the highest leaching potential when rainwater pH is neutral. Conversely, cadmium (Cd), lead (Pb), and manganese (Mn) metals are more prone to leaching in acidic environments. The leaching of iron (Fe), cobalt (Co), copper (Cu), and nickel (Ni) remains relatively constant in both acidic and alkaline conditions. Notably, at a pH of 5, the leaching order of heavy metals was observed as

Co > Cd > Pb > Zn > Cu > Mg > Ni > Mn > Fe.

Furthermore, the washing of EAFD using 1 molar and 3 molar concentrations of hydrochloric acid (HCl), nitric acid (HNO₃), and sulfuric acid (H₂SO₄) demonstrated that H₂SO₄ had a more pronounced effect on metal leaching compared to HNO₃ and HCl. Increasing the concentration of these acids from 1 to 3 molar resulted in higher percentages of metal washing. However, the concentration of H₂SO₄ inversely affected the leaching of Cd. Pb and Ni exhibited the lowest leaching levels among the studied metals.

The physicochemical properties analysis of dust from the steel factory's arc furnace highlights the importance of recycling, reuse, and proper management and maintenance of this waste. Implementing measures such as avoiding wind distribution and reducing leaching through rainfall can be achieved by applying a layer of oil mulch to the surface of collected EAFD, enhancing adhesion and reducing permeability.

Overall, this study provides valuable insights for reducing waste disposal, preserving raw materials, managing energy and water resources, and mitigating soil and groundwater pollution associated with EAFD.

Data Availability

The data used to support the research findings are available from the corresponding author upon request.

Conflicts of Interest

We certify that there is no actual or potential conflict of interest in relation to this study.

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