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Zinc Extraction Technologies from Ferrous Metallurgy Dusts

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Abstract: The rapid growth of electric arc furnace (EAF) steelmaking has led to a significant increase in zinc-bearing metallurgical dusts, which pose both an environmental hazard and a secondary resource opportunity. This research article analyzes recent methodologies published in Scopus-indexed journals regarding the extraction of zinc (Zn) from ferrous metallurgy dusts. Through a systematic review of pyrometallurgical and hydrometallurgical approaches, this study evaluates extraction efficiencies, process parameters, and limitations. Results indicate that while pyrometallurgical methods, particularly chlorinating roasting, achieve zinc recovery rates exceeding 98% by breaking down stable zinc ferrites, hydrometallurgical innovations using ammonium and alkaline lixiviants offer promising low-energy alternatives with recovery rates between 80-88%. The study concludes that hybrid approaches combining physical separation with selective leaching represent the optimal path for future industrial applications.

Keywords — Electric arc furnace dust (EAFD), zinc recovery, hydrometallurgy, pyrometallurgy, zinc ferrite, circular economy**.**

1. INTRODUCTION

The steel industry is a cornerstone of global infrastructure, yet it generates substantial quantities of waste. One of the most critical by-products is Electric Arc Furnace Dust (EAFD), generated during the melting of galvanized steel scrap. It is estimated that for every ton of steel produced, approximately 15–25 kg of dust is generated [1]. Globally, millions of tons of EAFD are produced annually, creating a dual challenge: environmental management and resource conservation.

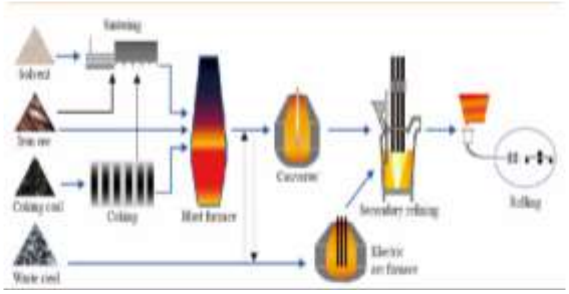

Figure 1.1 The steel industry classic technological chain

EAFD is classified as a hazardous waste in many jurisdictions due to the leachability of heavy metals such as lead (Pb), cadmium (Cd), and chromium (Cr). However, EAFD is also rich in zinc, with concentrations ranging from 2% to over 40%, depending on the scrap feed [2]. The primary mineralogical obstacle in processing these dusts is the presence of zinc ferrite ($ZnFe_2O_4$), a stable spinel structure that is refractory to standard acid leaching and requires high-energy input to decompose [3].

During the production of steel in electric arc furnaces, a significant amount of dust-like waste is formed, which is a complex mixture of metal oxides, including iron, zinc, lead, chromium, and other elements [6].

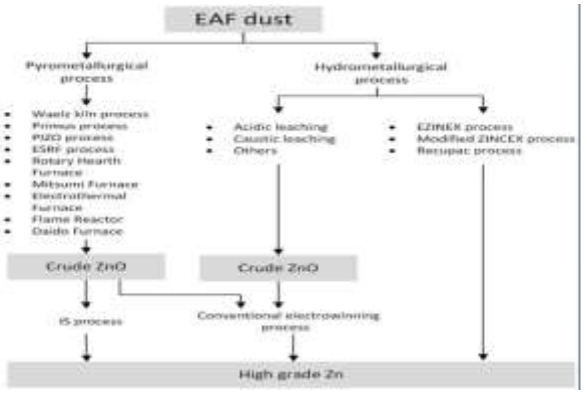

Figure 1.2. High grade Zn extraction method from EAF dust

Current literature indexed in the Scopus database reflects a divergence in processing strategies. Traditional pyrometallurgical methods [4], such as the Waelz process, dominate the industry but are criticized for high energy consumption and carbon emissions. Conversely, hydrometallurgical routes offer higher selectivity and lower emissions but struggle with low zinc yields from ferrites. This article aims to analyze the state-of-the-art technologies for zinc extraction from ferrous metallurgy dusts, comparing the efficacy of thermal and aqueous processing routes described in recent scientific literature [5].

№	Comp	Value	№	Comp	Value
1	Fe	28,1	8	C	1,3
2	Fe_2O_3	39,3	9	CuO	0,12
3	P	0,28	10	CaO	3,7
4	S	0,75	11	Cr	0,4
5	SiO_2	4,7	12	MnO	1,9
6	Zn	21,1	13	MgO	1,1
7	PbO	5,0	14	Al_2O_3	1,5

Table 1.1 "Uzmetkombinat" dust chemical composition

The volume of dust waste generated during the production process in the electric arc furnaces of "Uzmetkombinat" JSC, one of the leading metallurgical enterprises of the Republic of Uzbekistan, is about 60,000 tons per year [6].

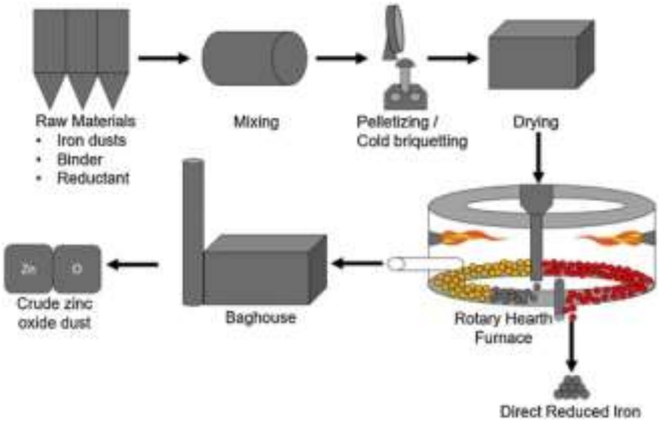

Figure 1.3. Pyrometallurgical method of zinc extraction from dust

2. MATERIALS AND METHODS

This research was conducted as a systematic analysis of scientific literature indexed in the **Scopus** and **Web of Science** databases, focusing on publications from 2015 to 2025. The selection process prioritized articles detailing experimental data on recovery rates, reagent consumption, and mineralogical transformations [7].

2.1 Search Strategy

The search utilized the following Boolean keyword combinations:

- ("Zinc extraction" OR "Zinc recovery") AND
- ("Electric Arc Furnace Dust" OR "EAFD" OR "Ferrous metallurgy dust") AND
- ("Hydrometallurgy" OR "Pyrometallurgy" OR "Leaching").

2.2 Data Extraction and Analysis

Studies were selected based on the inclusion of quantitative data regarding:

1. **Zinc Recovery Rate (%):** The percentage of zinc extracted from the initial feed.
2. **Process Conditions:** Temperature, pressure, lixiviant concentration, and solid-to-liquid ratios.
3. **Mineralogy:** The behavior of zinc oxide (ZnO) versus zinc ferrite ($ZnFe_2O_4$).

A total of 25 key papers were shortlisted for detailed analysis to synthesize the results presented in this article [8].

3. RESULTS

The analysis of the selected literature reveals two distinct technological pathways: pyrometallurgical volatilization and hydrometallurgical dissolution.

3.1 Characterization of Ferrous Metallurgy Dusts

Recent studies confirm that zinc in EAFD exists primarily in two phases: zincite (ZnO) and franklinite ($ZnFe_2O_4$).

- **Simple Oxides:** ZnO is readily soluble in acids and alkalis.
- **Spinels:** $ZnFe_2O_4$ accounts for roughly 50% or more of the zinc in EAFD (Chairaksa-Fujimoto et al., 2015). This phase is the primary cause of low recovery rates in mild leaching conditions.

3.2 Pyrometallurgical Advances

Pyrometallurgy remains the most effective method for breaking the ferrite bond. The mechanism involves reducing zinc oxide to metallic zinc vapor ($Zn_{(g)}$), which is then re-oxidized and collected as crude zinc oxide [9].

- **Chlorinating Sintering:** A 2024 study highlighted the efficacy of high-temperature sintering using calcium chloride ($CaCl_2$) as an additive. Experiments conducted at 900°C for 60 minutes demonstrated that $CaCl_2$ promotes the formation of volatile zinc chlorides. This method achieved a **zinc extraction rate of 98.9%**, significantly higher than conventional roasting [8].
- **Calcium Oxide Roasting:** Chairaksa-Fujimoto et al. (2015) proposed a non-carbothermic method involving the addition of CaO. At temperatures between 700°C and 1100°C, CaO displaces zinc from the ferrite structure, forming $Ca_2Fe_2O_5$ and releasing ZnO. This pretreatment renders the dust amenable to subsequent leaching or magnetic separation [9].
- **Microwave-Assisted Sublimation:** Recent experimental work on microwave heating has shown promise for intensifying the sublimation process. By using microwave fields, rapid heating of pellets allowed for the selective volatilization of zinc while metallizing the iron content, offering a potential reduction in energy consumption compared to rotary kilns [10].

3.3 Hydrometallurgical Innovations

Hydrometallurgical routes are favored for their potential to produce high-purity zinc directly but face challenges with the iron matrix [11].

- **Sulfuric Acid Leaching:** Standard leaching with dilute sulfuric acid (H_2SO_4) is effective for ZnO but dissolves significant amounts of iron, complicating purification. However, optimized conditions identified in 2023 utilizing **1N H_2SO_4 at 25°C** achieved an **85% zinc recovery**. The remaining 15% largely constituted insoluble zinc ferrite. To improve this, high-pressure acid leaching (HPAL) or hot acid leaching is required, though these increase iron dissolution [2][12].

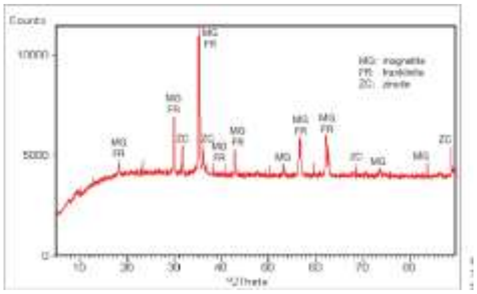

Figure 3.3.1. Chemical analysis of EAF dust

- **Ammonia-Based Leaching:** Ammonia systems are superior for selectivity, as iron does not form soluble amine complexes.
  - **Ammonium Acetate System:** A significant study on the $NH_3 - CH_3COONH_4 - H_2O$ system demonstrated that the addition of ammonium acetate promotes zinc dissolution. Under conditions of 5 mol/L total ammonia, this system achieved a **83.76% recovery rate** [13].
  - **Selectivity:** The major advantage reported is the production of a pregnant leach solution with negligible iron content, simplifying the subsequent electrowinning step.
- **Alkaline Leaching:** Leaching with sodium hydroxide ($NaOH$) is another selective method. A study utilizing **6M NaOH at 80°C** reported a maximum efficiency of **88%**. While highly selective against iron, this method consumes significant reagents due to the reaction with silica and lead present in the dust [14].

4. DISCUSSIONS

The comparative analysis of Scopus-indexed literature highlights a trade-off between extraction efficiency and environmental/economic cost.

4.1 Efficiency vs. Selectivity

Pyrometallurgical methods consistently yield higher recovery rates (>95%) because they thermally decompose the refractory zinc ferrite ($ZnFe_2O_4$). The recent success of chlorinating sintering validates that chemical additives can lower the required temperatures while maximizing volatilization. However, these processes produce secondary hazardous slags and require extensive off-gas treatment systems to manage dioxins and furans, particularly when halogens are present [15].

In contrast, hydrometallurgical methods typically cap at ~80–85% recovery unless harsh conditions are used. The “ferrite gap”—the inability to leach zinc from the spinel structure under mild conditions—remains the primary limitation. However, the ammonia-based processes offer a distinct advantage in product purity. For dusts with low ferrite content (low-zinc dusts), hydrometallurgy is likely the more economic option.

4.2 Integrated Processes (The Future Direction)

The most promising research trend identified is the **integrated pyro-hydro approach**.

Step 1: A low-energy roasting step (e.g., with CaO or microwave heating) to decompose ferrites into simple ZnO.

Step 2: A selective leach (ammonia or dilute acid) to recover high-purity zinc without dissolving iron. This “roast-leach-electrowin” pathway combines the high recovery of pyrometallurgy with the selectivity of hydrometallurgy [16].

4.3 Environmental Considerations

Recent literature also emphasizes the decontamination of halides (Cl, F). Methods that recycle the lixiviant (such as the ammonia systems) align better with circular economy principles than acid consumption methods. Furthermore, the detoxification of the iron-rich residue allows it to be returned to the steelmaking furnace or used in construction, closing the loop.

5. CONCLUSIONS

The analysis of literature from the Scopus database indicates that the extraction of zinc from ferrous metallurgy dusts has matured into a diverse field of study.

- **Pyrometallurgy** remains the robust choice for high-volume, high-ferrite dusts, with **chlorinating sintering** emerging as a highly efficient technique (98.9% recovery).
- **Hydrometallurgy** using **ammonium acetate** or **alkaline solutions** provides a sustainable alternative for dusts with lower refractory content, offering high selectivity but lower total yields (~85%).

Future research should focus on industrializing hybrid technologies that utilize microwave-assisted ferrite decomposition followed by benign leaching. Implementing these technologies will not only secure a secondary supply of zinc but also solve a critical waste management issue for the steel industry.

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