

Current Status and Prospects of the Acid Leaching Process for Zinc from Zinc-Containing Steel Metallurgical Dust

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Abstract: The steel industry is a cornerstone of the national economy. The entire metallurgical process generates vast quantities of dust, accounting for approximately 8% to 12% of crude steel output, with annual domestic production exceeding 100 million tonnes. As this dust is rich in valuable metals such as zinc and iron, whilst also containing harmful heavy metals such as lead and cadmium, it presents both resource value and environmental risks. Due to their high selectivity, low energy consumption and high product purity, hydrometallurgical processing technologies have become a research focus for the resource recovery of zinc-containing dust. This paper provides a systematic review of the progress in processes for the wet extraction of zinc from steel metallurgical dust. It first outlines the sources and physicochemical properties of zinc-containing dust, then introduces research developments in acid leaching for zinc extraction, and finally compares and analyses the technical characteristics and limitations of different acid leaching processes for zinc extraction, whilst offering an outlook on future technological development directions.

Keywords: Steel metallurgical dust; Wet metallurgy; Leaching process; Zinc metal extraction.

1. Introduction

As the fundamental sector of the national economy, the steel industry is a major contributor to total industrial output value and employment, and serves as a key indicator of a nation's level of industrialisation and comprehensive national strength. From 2000 to 2023, global crude steel production has generally shown an upward trend, with China's crude steel output reaching 1.019 billion tonnes in 2023. The production processes of steel enterprises generate large quantities of steel metallurgical dust. Total dust generation across the entire production process accounts for approximately 8%–12% of crude steel output, with domestic steel metallurgical dust generation exceeding 100 million tonnes [1]. As a hazardous solid waste generated by the steel industry, blast furnace metallurgical dust possesses significant potential value due to its substantial zinc (present in forms such as zinc oxide and zinc ferrite) and iron content; however, it also contains heavy metals such as lead and cadmium, presenting dual characteristics of resource value and environmental risk [2-3].

Zinc is a vital strategic resource, widely used in numerous sectors including metallurgy, machinery, construction and batteries [4]. With the continuous growth in global demand for zinc and the ongoing expansion of smelting capacity, zinc resources are increasingly facing the challenge of depletion. Consequently, the resource recovery of zinc-containing metallurgical solid waste has become a crucial pathway to achieving sustainable development of the national economy. Processes for treating zinc-containing iron and steel metallurgical dust fall into two categories: pyrometallurgical techniques, which utilise rotary kilns, rotary hearth furnaces and similar processes to achieve the efficient recycling of zinc through high-temperature metallurgical reactions; and hydrometallurgical techniques, which rely on acid-base solutions to selectively leach target metals. Pyrometallurgical

processing is currently one of the primary technologies for the resource recovery of metallurgical dust. It involves high-temperature heating under a reducing atmosphere to selectively reduce zinc-containing oxides into metallic zinc vapour, thereby achieving the separation and enrichment of zinc and iron. However, this method suffers from issues such as high energy consumption, low comprehensive resource utilisation rates, and significant carbon dioxide emissions [5]. Compared to pyrometallurgical methods, hydrometallurgical methods are gradually becoming a hot topic in zinc recovery research due to their advantages of higher selectivity, lower energy consumption and higher product purity. This technology achieves efficient zinc leaching through steps such as roasting, leaching, purification and electrowinning (RLE) [6].

This paper firstly outlines the sources and primary constituents of iron and steel metallurgical dust, followed by a discussion of the technical principles, research methods and progress in the hydrometallurgical extraction of zinc from such dust. Finally, it provides a comparative analysis of the technical advantages and challenges associated with this process, aiming to offer technical guidance for the resource utilisation of iron and steel metallurgical dust.

2. Sources and Main Constituents of Iron and Steel Metallurgical Dust

Steel metallurgical dust comprises sintering dust, blast furnace dust, converter dust and electric arc furnace (EAF) dust generated during steel production via the 'blast furnace–converter' long-process metallurgical routes and the 'melting reduction–electric furnace' short-process metallurgical routes [7-8]. The chemical composition of iron and steel metallurgical dust varies to some extent depending on the production process, primarily reflected in its physicochemical properties and the occurrence states of valuable metals [9].

Therefore, adopting appropriate methods to treat this metallurgical dust and convert the zinc contained therein into high-value-added resource products is key to achieving both environmental and economic development.

Table 1 shows the main components of iron and steel metallurgical dust [7]. As shown in Table 1, various types of iron and steel metallurgical dust are rich in valuable metals

Table 1. Main components of steel metallurgical dust %[7]

Sample name	TFe	SiO ₂	CaO	MgO	Al ₂ O ₃	Zn	C
Sintering machine head dust	18.553	4.449	6.948	3.550	2.179	0.702	—
Ash from the slag trough	49.865	6.972	7.109	2.399	3.111	—	—
Blast furnace baghouse dust	19.190	7.650	8.210	2.100	3.230	6.790	18.020
Gravity dust collector dust	34.030	—	—	—	—	0.450	28.700
Dust from ironworks	33.340	3.200	1.690	0.480	1.630	—	—
Converter primary ash	54.770	2.580	13.530	1.650	1.780	0.960	—
Converter secondary ash	60.610	3.100	1.300	0.720	1.390	5.920	—
Electric arc furnace (EAF) dust	42.880	2.620	12.950	1.250	0.550	9.850	1.350

3. Wet Treatment Process

3.1. Eh-pH Diagram for the Wet Treatment of Steel Metallurgical Dust

Eh-pH diagrams are a key basis for studying the thermodynamics of liquid-phase reactions. Based on the Eh-pH diagrams shown in Figures 1 and 2 for the Fe-Zn-H₂O system at 200 °C [10] and the Zn, Pb, Al, Sn, Bi, Cd-H₂O system at 25 °C [11], it can be concluded that as pH increases, most metal ions gradually hydrolyse to form precipitates, although the pH threshold for precipitation varies depending on the metal. Zn²⁺ readily forms Zn(OH)₂ or ZnO; Fe²⁺/Fe³⁺ is soluble at lower pH values, whilst at higher pH values it transforms into Fe₃O₄ or Fe₂O₃; Cd²⁺ and Pb²⁺ form Cd(OH)₂, Pb(OH)₂ or PbO₂ respectively in the alkaline region. Thermodynamic analysis based on the Eh-pH diagram can systematically reveal the transformation behavior of Zn, Fe, Cd and Pb under different acid-base and redox conditions, providing an important theoretical basis for the wet treatment of steel metallurgical dust.

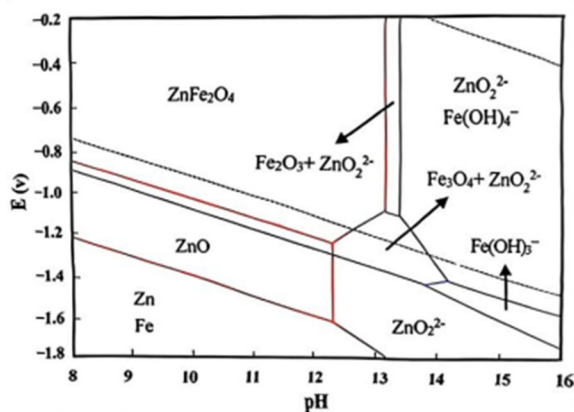


Figure 1. Eh-pH diagram of the Fe-Zn-H₂O system at 200 °C [10]

such as zinc and iron, as well as a significant amount of alkali metals. Electric arc furnace (EAF) dust has a higher zinc content; this is because electric furnace smelting employs a short-process metallurgical method using scrap steel as raw material. In contrast, traditional smelting processes still predominantly rely on the long-process method, resulting in lower zinc and higher iron content in the metallurgical dust.

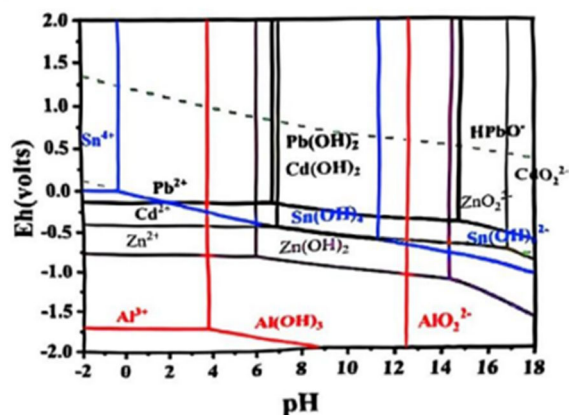


Figure 2. Eh-pH plot for the Zn, Pb, Al, Sn, Bi, Cd-H₂O system at 25 °C [11]

3.2. Current Status of Research on Wet Processing Technologies for Zinc Recovery from Steel Dust

Wet leaching technologies for zinc recovery from iron and steel metallurgical dust can be broadly categorised, based on the solvent system, into acidic, alkaline and ammonia leaching processes. In recent years, new methods such as low-melting-point solvent (DES) leaching have also been developed [12-13].

3.2.1. Acidic Leaching

The acid leaching method has consistently occupied a dominant position due to its mature process, high leaching efficiency and good selectivity. Depending on the solvent system used, acid leaching is primarily divided into two categories: inorganic acid leaching (e.g. hydrochloric acid, sulfuric acid) and organic acid leaching.

3.2.1.1 Hydrochloric Acid Leaching

As a commonly used hydrometallurgical technique, the core principle of hydrochloric acid leaching is the conversion of zinc into soluble zinc chloride (ZnCl₂) through the chemical reaction between hydrochloric acid and zinc

compounds (such as ZnO, ZnS, and ZnCO₃). Research has shown that the rate of zinc dissolution in hydrochloric acid follows a surface chemical reaction mechanism [14], and that zinc leaching in acidic media is a diffusion-controlled process [15], with the reaction rate being influenced by various mass transfer factors such as temperature, agitation intensity and solid-to-liquid ratio.

In the hydrochloric acid leaching of zinc-containing iron and steel dust, researchers have focused primarily on controlling operational parameters such as reaction temperature, leaching time and leaching agent concentration to address the challenge of co-dissolution of impurities and to improve leaching efficiency. For example, Trpcevska et al. [16] proposed a process for the efficient leaching and recovery of zinc using hydrochloric acid. By precisely controlling the leaching time to 30 minutes, they effectively suppressed the excessive dissolution of impurities (Pb, Cu) and achieved a zinc recovery rate of nearly 100%. Furthermore, the optimal leaching temperature for this process was 20 °C, offering the advantage of low energy consumption. Luo et al. [17] employed a NaCl-HCl-H₂O system to selectively leach zinc from blast furnace dust. Under specific optimised conditions (NaCl concentration of 3 mol/L, HCl concentration of 0.25 mol/L, and pH of 4), they achieved the effective dissolution of zinc oxide (ZnO) and zinc sulphide (ZnS), whilst zinc-iron spinel (ZnFe₂O₄) was not leached out and was retained in the residue together with iron oxide (Fe₂O₃), thereby achieving effective separation of zinc and iron [18].

Hydrochloric acid leaching of zinc offers the advantages of a fast reaction rate and strong dissolution capacity; however, this leaching process is prone to the co-dissolution of various metallic impurities. Future research should focus on optimising the leaching process; adjusting the solution pH and optimising the potential can simultaneously achieve the efficient oxidative dissolution of the target phase and the suppression of impurity element behavior to selectively leach zinc. Chloride ions are characterised by their ability to destroy passivation films and their strong corrosiveness; therefore, the corrosion resistance of the equipment also needs to be further improved.

3.2.1.2 Sulphuric acid leaching

Compared with other acids, sulphuric acid offers the advantages of high efficiency, low cost and easy availability, and has been widely used for the extraction of zinc from zinc-bearing metallurgical dust.

Kul et al. [19] investigated the influence of various leaching parameters on the leaching of zinc and iron from electric arc furnace dust, and employed a three-level Box-Behnken design to model and optimise the parameters for selective zinc leaching from electric arc furnace dust. Under optimal leaching conditions, the maximum zinc recovery rate was 79.09%, whilst the minimum recovery rate for iron was 4.08%. They also determined that acid concentration and leaching temperature were the most effective parameters for iron leaching recovery. He Lingyu [20] conducted leaching experiments on electric furnace dust under various conditions; at a temperature of 85 °C and a sulphuric acid concentration of 1 mol/L, the leaching rates for Zn and Fe were 94.8% and 95.7%, respectively. Research has found that when the sulphuric acid concentration is below 100 g/L, the leaching rate of zinc is low. When the sulphuric acid concentration exceeds 100 g/L, the leaching rate of iron increases rapidly with rising concentration. This behaviour is attributed to the

dissolution of zinc ferrite—formed during the high-temperature calcination of zinc-containing steel metallurgical dust—under conditions of high temperature and high sulphuric acid concentration [21]. Excessive leaching of iron leads to a series of problems, including the formation of large amounts of colloids during the leaching process, contamination of purification processes, soaring production costs, and a decline in product quality. Based on the principle of hydrolysis and precipitation of iron, researchers have removed iron from the solution by adjusting the pH and employing the potassium ferrate method, goethite method, and hematite method, thereby achieving effective control and separation of zinc and iron in the leachate [22–24]. Montenegro V et al. [25] improved the leaching process by applying a three-stage leaching process under high pressure to washed electric furnace dust. In the first stage, sulphuric acid solutions of 2N and 3N concentrations were used, with the temperature controlled at 25°C; the second and third stages involved two-stage counter-current leaching at 95°C; under these conditions, almost all zinc ferrite was dissolved within 120 minutes, achieving extraction rates of 97% for zinc and cadmium, whilst 99.7% of the lead remained undissolved in the leaching residue in the form of lead sulphate. Researchers have also proposed the use of enhanced pre-treatment techniques to improve the leaching efficiency of metallic zinc during the sulphuric acid leaching process. Trifunović et al. [26] applied pre-treatment to experiments involving the sulphuric acid leaching of electric furnace dust; the application of pre-treatment reduced the volume of hazardous waste by 6% compared to the initial volume, and compared to the untreated sample, the application of pre-treatment increased the zinc leaching efficiency by 9%. Zheng X et al. [27–28] conducted experimental studies on the extraction of zinc from zinc oxide dust using sonically enhanced sulphuric acid leaching, investigating the influence of various process parameters on the zinc leaching rate. Compared with the conventional leaching method (leaching rate of 85.36%), the ultrasonic method increased the zinc leaching rate by 5.8%.

The sulphuric acid leaching process has become an industrially established method for treating dust from the iron and steel metallurgy sector due to its high leaching efficiency and simplicity of operation. However, the process results in significant dissolution of impurities, leading to poor selectivity for the target metal, zinc. Furthermore, this process is associated with issues such as large volumes of leaching residue and complex subsequent treatment, whilst hot acid leaching also poses certain safety risks. These factors have limited its further adoption on an industrial scale.

3.2.1.3 Extraction with organic acids

The inorganic acid systems used in traditional hydrometallurgy face a range of challenges, including low selective leaching efficiency for target metals and environmental pollution; organic acids, however, have attracted widespread attention due to their unique mechanism of action in metal leaching. Unlike inorganic acid leaching, which relies primarily on hydrogen ion (H⁺) attack, organic acid leaching employs a dual mechanism involving both H⁺ dissolution and coordination dissolution.

Wang Jingxiu et al. [29] investigated the efficiency of six organic acids, including oxalic acid and citric acid, in leaching iron and zinc from converter dust; the study indicated that oxalic acid inhibited the leaching process due to its tendency

to form precipitates; citric acid, owing to its strong chelating ability, significantly promoted metal dissolution, but exhibited poor selectivity for zinc leaching. The satisfactory zinc leaching rates achieved by leaching zinc-bearing metallurgical dust with organic acids are primarily due to the highly leaching-resistant nature of zinc-iron spinel, the main form in which zinc is present in the dust. Pretreatment methods have demonstrated significant potential for improving the efficiency of organic acid leaching. Halli et al. [30] proposed a two-step solution (pretreatment + citric acid leaching), which involves converting zinc-iron spinel into soluble zinc oxides via pre-treatment, followed by selective leaching with citric acid at a low temperature of 40 °C. This process achieved a zinc dissolution rate of 99.8% under mild conditions, whilst limiting the iron leaching rate to below 10%. A schematic diagram of the mechanism of this method is shown in Figure 1. The synergistic effect of pre-treatment technology and organic acid leaching not only enhances leaching efficiency but also overcomes the drawback of poor selectivity in traditional acid leaching of metallurgical dust.

An analysis and comparison of current domestic and international processes for the wet extraction of zinc from steel metallurgical dust using organic acids reveals that organic acid leaching technology faces challenges such as high costs, low leaching efficiency and difficulties in recovering the organic acids. These factors are hindering the further development of its industrial application, and further research is required to achieve key breakthroughs.



Figure 4. Schematic diagram of the mechanism of alkaline roasting and citric acid leaching [30]

Consequently, the leaching efficiency of the acid leaching process depends not only on the type and concentration of the leaching agent; for different types of steel metallurgical dust, the use of appropriate pretreatment methods and precise

adjustment of leaching process parameters play a crucial role in altering the physical and chemical properties and improving leaching efficiency.

4. Comparative Analysis of Different Hydrometallurgical Leaching Processes

This paper provides a detailed account of research progress in hydrometallurgical zinc extraction technologies, with a particular focus on the latest developments in acid leaching. Conventional wet leaching processes suffer from issues such as high energy consumption and severe environmental pollution, which have limited their further industrial development. To meet the rapidly growing demand for zinc, future research should focus on optimising leaching processes and developing novel leaching agents to achieve efficient leaching and selective extraction of zinc. Based on the above analysis, this paper identifies key future development directions for wet leaching technologies targeting zinc-containing steel metallurgical dust, and offers recommendations for subsequent research:

Combining the physical properties of steel metallurgical dust with its Eh-pH diagram in liquid-phase reactions, conduct in-depth research into the stable Eh-pH ranges for zinc metal and other major impurity metals (iron, lead, cadmium) within specific leaching systems, and achieve stepwise selective leaching by adjusting the redox potential and pH; In the initial stages of material processing, enhanced pretreatment techniques such as mechanical activation and microwave treatment can be employed to disrupt the crystal structure of minerals and promote the breaking of chemical bonds, thereby improving leaching kinetics; further research should be conducted into the adsorption, dissociation, mass transfer and reaction kinetics on mineral surfaces in different leaching systems, revealing reaction pathways and rates at the atomic level to enhance leaching efficiency. However, conventional hydrometallurgical leaching processes suffer from poor selectivity and high equipment corrosion, which limits their further industrial development. Consequently, efforts should be intensified to develop valuable acid recovery technologies, overcome cost barriers, and promote the industrial application of organic acid leaching.

Table 2. Comparative Analysis of Hydrometallurgical Leaching Processes

System	Leaching Mechanism	Advantages	Disadvantages
Hydrochloric acid	Acid dissolution; Cl ⁻ complexation effect	High leaching efficiency; iron slag is easy to handle	Highly corrosive to equipment; produces chlorine gas
Sulfuric acid	Acid dissolution; Fe ³⁺ oxidation-regeneration	Low-cost raw materials, simple operation, suitable for large-scale application	Difficult to separate Zn and Fe; produces large amounts of iron slag
Organic acids	Acid dissolution; complexation dissolution	High selectivity, reducing purification difficulties; low toxicity, biodegradable	Slow reaction rate; organic acids are difficult to recover

5. Summary and Outlook

This paper provides a detailed account of recent research advances in hydrometallurgical zinc extraction, with a focus on the latest developments in acid leaching, sodium hydroxide leaching, ammonia leaching, and novel co-solvents. Conventional wet leaching processes suffer from high energy

consumption and severe environmental pollution, which limit their further industrial development. To meet the rapidly growing demand for zinc, future research should focus on optimizing leaching processes and developing new leaching agents to achieve efficient leaching and selective extraction of zinc. Based on the above analysis, this paper identifies key future development directions for wet leaching technologies

targeting zinc-containing steel metallurgical dust and provides recommendations for subsequent research:

Combining the physical properties of steel metallurgical dust with its Eh-pH profiles in liquid-phase reactions, conduct in-depth research on the stable Eh-pH ranges for zinc metal and other major impurity metals (iron, lead, cadmium) in specific leaching systems, and achieve stepwise selective leaching by adjusting the redox potential and pH; In the initial stages of material processing, enhanced pretreatment technologies such as mechanical activation and microwave treatment can be employed to disrupt the crystal structure of minerals and promote the breaking of chemical bonds, thereby improving leaching kinetics; conduct in-depth research on adsorption, dissociation, mass transfer, and reaction kinetics on mineral surfaces in different leaching systems, and reveal reaction pathways and rates at the atomic level to enhance leaching efficiency. However, conventional hydrometallurgical leaching processes suffer from poor selectivity and high equipment corrosion, limiting further industrial development. Moving forward, efforts should focus on developing valuable acid recovery technologies, overcoming cost barriers, and promoting the industrial application of organic acid leaching.

Eutectic solvents demonstrate immense potential in hydrometallurgy due to their high solubility and low volatility, but their high viscosity has become a bottleneck limiting large-scale application. In the future, techniques such as molecular dynamics simulations can be used to establish predictive models to guide the development of novel low-viscosity eutectic solvents. Eutectic solvents hold great promise for replacing traditional leaching processes in the treatment of complex steel metallurgical dust.

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Conflicts of Interest

The authors declare no conflict of interest.

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