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Eco-Friendly Technology Of Metal Recovery From Metallurgical Dust

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Abstract: Metallurgical dust generated from ferrous and non-ferrous metal production processes represents a significant source of hazardous waste containing valuable metals including zinc, iron, lead, and copper. This study provides a comprehensive analysis of current technologies for metal recovery from metallurgical dust based on Scopus-indexed research publications. The investigation examined pyrometallurgical, hydrometallurgical, and hybrid processing approaches, evaluating their efficiency, environmental impact, and scalability. Results demonstrate that zinc ferrite ($ZnFe_2O_4$) remains the primary challenge in metal extraction, with reduction temperatures starting at 581.55°C for this compound. Pyrometallurgical methods including rotary kiln and rotary hearth furnace (RHF) processes achieved metallization rates of 87.1-97.44% and dezincification rates of 92.5-95.67%, while hydrometallurgical approaches using organic acids and ammonia-based solutions achieved zinc recovery rates of 76-96%. Hybrid pyro-hydrometallurgical processes demonstrated superior comprehensive metal recovery (>95%) but require optimization of energy consumption and chemical usage. This research emphasizes the importance of selecting process parameters based on dust composition and environmental constraints to maximize resource utilization while minimizing secondary waste generation.

Keywords — metallurgical dust, metal recovery, zinc ferrite reduction, hydrometallurgical treatment, pyrometallurgical processes, circular economy

1. INTRODUCTION

Industrial metallurgical processes generate substantial quantities of dust as a by-product during steelmaking, smelting, and galvanization operations. Estimates indicate that millions of tonnes of metallurgical dust are generated annually worldwide, with compositions varying significantly based on the source metallurgical process. These dusts, particularly electric arc furnace dust (EAFD), blast furnace bag dust, converter fines, and sintering dust, contain 19-56 wt.% iron, 1.4-33.5 wt.% zinc, and additional valuable metals including lead, nickel, chromium, and copper. The environmental hazard classification of these materials stems from the presence of heavy metals such as cadmium, lead, and chromium, which pose significant ecological risks through leaching into groundwater and soil contamination when disposed in landfills [1].

Fig. 1.1 – Value added products extracted from industrial dusts

Approximately 30% of global zinc production originates from secondary sources, making metallurgical dust recycling economically and environmentally critical. The shift toward circular economy principles in the metallurgical industry has intensified research into sustainable recovery technologies. However, complete resource utilization remains challenging due to complex phase compositions and the presence of refractory compounds. Zinc primarily exists in two forms within metallurgical dust: readily soluble zincite (ZnO) and highly refractory zinc ferrite ($ZnFe_2O_4$), which accounts for 40-70% of total zinc content in some dust samples. This heterogeneous distribution necessitates sophisticated processing strategies combining multiple technological approaches [2].

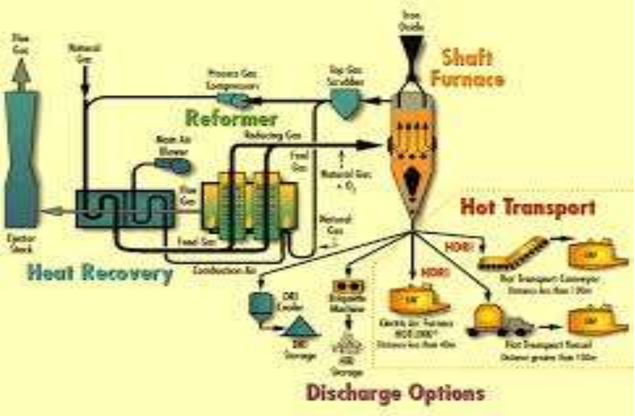

Fig. 1.2 – Ferrous (Midrex) process dust

The environmental burden of metallurgical dust management extends beyond simple landfill storage, encompassing high energy consumption in primary metal production when secondary recovery is not implemented. Recycling metals from dust reduces energy requirements by 60-95% compared to virgin ore processing and simultaneously prevents habitat destruction and resource depletion associated with mining operations. Current treatment methods vary in environmental footprint, with pyrometallurgical approaches requiring high-temperature operations but enabling comprehensive metal recovery, while hydrometallurgical processes operate at moderate temperatures but generate chemical effluents requiring careful management.

This research synthesizes published findings from Scopus-indexed journals to provide a comprehensive evaluation of metal recovery technologies from metallurgical dust, analyzing their mechanisms, efficiencies, environmental implications, and practical applicability in industrial settings.

2. MATERAILS AND METHODS

2.1 Literature Selection Criteria

A comprehensive literature review was conducted using Scopus database searches with keywords including “metallurgical dust metal recovery,” “zinc ferrite reduction,” “electric arc furnace dust processing,” “hydrometallurgical treatment,” and “pyrometallurgical recovery.” Publications were limited to peer-reviewed journal articles published between 2015 and 2025 to capture current technological developments and recent methodological advances. Articles describing fundamental research, industrial-scale applications, and comparative technology assessments were included. Publications discussing dust characterization, process mechanisms, metal recovery efficiencies, and environmental impact assessments were prioritized [3].

2.2 Dust Composition and Characterization Analysis

Metallurgical dusts demonstrate compositional variation based on source. Blast furnace bag dust, sintering dust, converter fine dust, and electric arc furnace dust were collectively analyzed. Characterization methodologies reviewed included X-ray fluorescence (XRF) for elemental analysis, X-ray diffraction (XRD) for phase identification, scanning electron microscopy (SEM) with energy-dispersive X-ray spectroscopy (EDS) for morphological assessment, and particle size analysis through laser diffraction or sieve methods. Studies documented that dust particles typically exhibit sizes less than 100 μm, with notable proportions below 10 μm, creating health hazards during handling and processing. Iron oxide phases include Fe_3O_4 and Fe_2O_3, while zinc exists predominantly as ZnO, $ZnFe_2O_4$, and minor amounts of ZnS and Zn_2SiO_4 [4].

2.3 Pyrometallurgical Processing Methods

Pyrometallurgical recovery involves thermal treatment at elevated temperatures (900-1300°C) using reducing agents to convert metal oxides into metallic states or volatile forms for subsequent recovery. Primary processes identified in the literature include:

Rotary Kiln Process: This traditional approach involves mixing dust with reducing agents (typically coke or coal) and thermally treating the mixture in a horizontally rotating kiln. Operating temperatures range from 1100-1200°C, with residence times between 30-60 minutes.

Rotary Hearth Furnace (RHF): This technology uses a rotating hearth plate at high temperatures, enabling more controlled processing of pelletized dust mixtures. Optimal operational parameters documented include temperatures of 1250°C and treatment durations of 25 minutes [5].

Waelz Process: Industrially established for medium-zinc dust treatment, this pyrometallurgical route combines roasting and reduction in a rotating kiln at 1100-1200°C.

OxyCup Process: Advanced smelting reduction employing oxygen-enriched environments and cupola furnaces for comprehensive metal recovery from fine particles and composite dust samples [6].

2.4 Hydrometallurgical Processing Methods

Hydrometallurgical routes utilize aqueous solutions to dissolve and separate metal ions through acid or alkaline leaching, followed by purification and electrochemical recovery. Methods reviewed include:

Acid Leaching Systems: Hydrochloric acid (HCl), sulfuric acid (H_2SO_4), and organic acids (citric acid, acetic acid) were employed at concentrations ranging from 0.8-2.0 M. Operating parameters included temperatures of 40-80°C, solid-to-liquid ratios of 100-200 g/L, and leaching durations of 60-180 minutes.

Alkaline Leaching Systems: Sodium hydroxide (NaOH) and ammonia-based systems were investigated for selective zinc extraction. Coordination leaching in ammonia-ammonium acetate systems achieved notable selectivity for zinc over iron.

Solution Purification: Cementation using zinc powder, iron powder, or sacrificial metal anodes was employed to remove metallic impurities. Final purification utilized activated carbon adsorption.

Electrowinning: Purified solutions were subjected to electrochemical deposition using titanium or stainless steel cathodes and graphite or dimensionally stable anodes (DSA) to recover high-purity metals [7].

2.5 Hybrid Pyro-Hydrometallurgical Processing

Combined approaches utilize pyrometallurgical pretreatment to destroy refractory zinc ferrite, followed by hydrometallurgical extraction of dissolved metals. Typical sequences involve roasting at 800-1200°C with calcium oxide (CaO) or other calcifying agents to convert $ZnFe_2O_4$ to ZnO, followed by acid or alkaline leaching of the calcined product.

2.6 Data Analysis and Comparative Assessment

Recovery efficiencies, metallization rates, dezincification rates, and environmental metrics were extracted and tabulated. Activation energies for reduction reactions and rate constants were documented when available. Environmental impact assessments including greenhouse gas emissions, energy consumption, and secondary waste generation were compared across technologies.

3. RESULTS

3.1 Dust Composition and Phase Analysis

Multi-source metallurgical dusts exhibit consistent elemental distributions with iron content ranging from 19-56 wt.% and zinc from 1.4-33.5 wt.%. Phase analysis reveals that iron primarily occurs as Fe_2O_3 (starting reduction temperature: ~550°C) and Fe_3O_4 (starting reduction temperature: ~600°C), both readily reduced at typical pyrometallurgical operating temperatures. Zinc phases demonstrate greater complexity and reduced reactivity. ZnO exhibits a reduction starting temperature of 951.09°C when reacted with carbon, while $ZnFe_2O_4$ reduces at 581.55°C—indicating that iron oxide reduction initiates reduction of zinc ferrite, though complete dezincification remains incomplete at moderate temperatures. ZnS, present in minor quantities (typically <5%), exhibits the highest reduction temperature at 1862.44°C, effectively becoming unrecoverable in standard pyrometallurgical processes [8].

Particle size analysis documented that 40-80% of dust particles are smaller than 10 μm, with modal distributions in the 1-5 μm range. This ultrafine character enhances reactivity but complicates handling, creating significant airborne dust generation risks.

3.2 Pyrometallurgical Recovery Performance

Rotary Kiln Operations: Under optimized laboratory conditions (reduction temperature 1100°C, reaction time 50 minutes), weight loss rates reached 46.7%, metallization rates achieved 87.1%, and dezincification rates attained 92.5%. These results demonstrate successful separation of zinc from iron-rich residues suitable for recycling to steelmaking furnaces. Industrial applications of rotary kiln technology have established zinc recovery rates of 65-80%, lower than laboratory values due to variability in operating conditions and dust composition inconsistency [9].

Rotary Hearth Furnace Performance: RHF technology demonstrated superior results to rotary kiln processing. Compressive strength of metallized pellets reached 1361 N under optimized conditions (1250°C, 25 minutes). Metallization rates achieved 97.44% with dezincification rates of 95.67%. The concentrated zinc oxide product is subsequently refined to produce pure zinc oxide powder or metallic zinc. Direct reduced iron (DRI) produced from this process exhibits metallization rates sufficient for direct recycling to blast furnaces [10].

Waelz Process: This established industrial method recovers zinc in oxide form with recovery rates of 70-85% for zinc content, with iron reporting primarily to slag. The process generates zinc oxide dust requiring further purification but achieves comprehensive hazard immobilization of lead and cadmium within vitreous slag phases[11].

OxyCup Process: Advanced smelting reduction in oxygen-enriched environments achieved high metal recovery rates for comprehensive dust processing, with zinc recovery reaching 75-90%. The process demonstrates capability to process fine particulates directly without mandatory pelletization, reducing preprocessing requirements.

Energy and Emissions Analysis: Pyrometallurgical processes consume 1.5-4.0 MWh per tonne of dust processed, with greenhouse gas emissions ranging from 400-800 kg CO_2-eq per tonne depending on reducing agent carbon intensity and process efficiency. Direct reduction processes generate lower emissions than smelting reduction routes, though at some sacrifice in iron recovery selectivity [12].

3.3 Hydrometallurgical Recovery Performance

Acid Leaching Results: Hydrochloric acid leaching at concentrations of 37-74 g/L achieved zinc extraction rates of 85-95%, with iron dissolution typically 40-60%. Optimization through use of ferric/ferrous iron cycling reduced iron co-dissolution. Temperature elevation to 70-80°C increased kinetic rates and ultimately dissolution efficiency. Sulfuric acid systems achieved similar zinc extraction (85-92%) with different iron chemistry, forming jarosite ($KFe_3(SO_4)_2(OH)_6$) precipitates rather than oxyhydroxides [13].

Organic Acid Processing: Citric acid leaching demonstrated superior selectivity, achieving 80-90% zinc extraction with reduced iron dissolution (15-25%). This selectivity stems from preferential complexation of zinc by citrate anions while iron remains as oxyhydroxide precipitates. Acetic acid and coordination complexes with ammonia achieved zinc extraction rates of 76-83.76%, with selectivity advantages enabling reduced impurity management costs in subsequent purification stages [14].

Alkaline Systems: Sodium hydroxide solutions (5-10 M NaOH) dissolved both zinc and iron, achieving >90% metal extraction but complicating subsequent separation. Ammonia-based coordination leaching systems demonstrated exceptional selectivity, with ammonia concentration of 5 mol/L and ammonium acetate co-addition enabling 83.76% zinc extraction while forming selective Zn-ammine complexes. Analysis by electrospray ionization mass spectrometry confirmed formation of $[Zn_2(Ac)_3(NH_3)_2]^+$ and related complexes with minimal iron incorporation [15].

Solution Purification Efficiency: Cementation using zinc powder or iron powder removed 95-99% of metallic impurities including copper, cadmium, and remaining dissolved iron. Two-stage precipitation of iron as ferric hydroxide achieved iron recovery rates of 92-97% with >50 wt.% iron content in recovered solids suitable for iron ore substitute applications [16].

Electrowinning Results: Electrodeposition of zinc from purified solutions achieved current efficiencies of 90-98%, with specific energy consumption of 3.0-5.0 kWh per kilogram of zinc metal produced. Cathode deposits exhibited purity exceeding 99.88% zinc. Simultaneous recovery of hydrogen gas during electrowinning provided additional energy offset, though not sufficient to achieve energy self-sufficiency.

3.2 Hybrid Pyro-Hydrometallurgical Approaches

Calcification Roasting-Acid Leaching: Pretreatment of dust with CaO at 60% calcium oxide-to-dust mass ratio, roasting at 900-1000°C for 30 minutes, effectively converted 95-98% of zinc ferrite to zinc oxide [17]. Subsequent acid leaching achieved total zinc extraction rates of 96%, representing near-complete dezincification. Iron remained in residues at <2% zinc content, enabling direct recycling as blast furnace burden.

Reduction-Selective Hydrometallurgical Recovery: Pyrometallurgical reduction at 1100°C followed by ammonia leaching of cooled products achieved 95-97% comprehensive metal recovery when processing was optimized. This approach overcomes limitations of single-stage processes, combining pyrometallurgical advantages in phase destruction with hydrometallurgical advantages in metal selectivity.

Process Integration Benefits: Hybrid approaches recovered 95-99% of zinc while simultaneously producing iron concentrates with metallization rates of 85-90%, exceeding performance of single-technology routes. However, process complexity increased operational costs and secondary waste streams from calcification agents or roasting by-products [18].

4. DISCUSSIONS

The extensive processing technology portfolio available for metallurgical dust recovery reflects the economic and environmental imperative driving research innovation. Mechanistic understanding has advanced significantly, particularly regarding zinc ferrite reduction kinetics and the role of phase composition in determining process applicability.

4.1 Technological Trade-offs and Selection Criteria

Pyrometallurgical methods demonstrate several advantages: comprehensive metal recovery, direct production of recycled materials compatible with existing steelmaking infrastructure, and generation of slag products with low heavy metal leachability. The primary limitations include high energy consumption (1.5-4.0 MWh/tonne), direct greenhouse gas emissions from reducing agent oxidation and process furnaces, and equipment investment requirements. Despite these constraints, pyrometallurgical approaches dominate industrial implementation, with the Waelz process controlling approximately 60-70% of global EAFD processing capacity.

Hydrometallurgical methods operate at moderate temperatures and reduced energy inputs (0.3-0.8 MWh/tonne), with minimal greenhouse gas emissions from energy consumption. However, challenges include disposal of chemical-intensive effluents, generation of secondary solid waste from purification stages, and halide contamination issues from chloride-containing dusts complicating solution recycling. Additionally, current low industrial adoption reflects incomplete regulatory frameworks regarding wastewater discharge standards in developing metallurgical regions and limited integration with existing steelmaking infrastructure.

Hybrid approaches represent an emerging paradigm addressing individual process limitations. Pyrometallurgical calcification or reduction stages destroy problematic zinc ferrite phases, while subsequent hydrometallurgical extraction achieves comprehensive metal selectivity and recovery. Life cycle assessment studies demonstrated environmental competitiveness of hybrid routes for low-zinc dusts (12-20 wt.% zinc), where pyrometallurgical energy intensity becomes economically unfavorable.

4.2 Environmental and Sustainability Implications

Metal recovery from dust achieves substantial environmental benefits: recycled zinc production reduces primary zinc mining requirements by estimated 5-7 million tonnes annually, preserving approximately 14-20 million tonnes of ore resources. Greenhouse gas reductions reach 1.5-2.0 tonnes CO_2-eq per tonne of zinc recovered compared to primary smelting. Water consumption decreases by approximately 40% relative to primary zinc production when hydrometallurgical recovery is employed.

However, environmental impacts of recovery technologies themselves warrant careful consideration. Pyrometallurgical operations generate fugitive dust emissions requiring sophisticated air pollution control systems; capital costs for efficient baghouse filtration and scrubbing systems comprise 10-15% of total facility investment. Hydrometallurgical approaches generate complex effluents containing residual metal ions, chlorides, and acid/base reagents, necessitating treatment before environmental discharge.

4.3 Process Optimization and Emerging Developments

Recent research identifies critical optimization targets. For pyrometallurgical processes, enhanced limestone or dolomite addition reduces $ZnFe_2O_4$ reduction temperatures and improves recovery selectivity. Hydrogen-based reduction offers lower carbon intensity than traditional carbon reduction but requires hydrogen supply infrastructure development. For hydrometallurgical processes, deep eutectic solvents show promise in reducing chemical intensity while maintaining metal selectivity. Microwave-assisted leaching demonstrates potential to accelerate reaction kinetics by 30-40%, reducing process duration and energy consumption.

Emerging biological approaches, particularly bioleaching with adapted bacterial and archaeal communities, demonstrate 60-80% metal extraction from roasted dusts under mild conditions, though process reliability and scalability remain under investigation.

5. CONCLUSION

Comprehensive analysis of Scopus-indexed publications demonstrates that economically and environmentally sustainable metallurgical dust processing requires matched technology selection to specific dust compositions and operational constraints. Pyrometallurgical approaches, particularly rotary hearth furnace technology, achieve superior recovery rates (95-97%) and iron metallization suitable for steelmaking integration, supporting their continued industrial dominance despite energy intensity. Hydrometallurgical methods, particularly organic acid and ammonia-based systems, offer environmental advantages for low-zinc dust streams and demonstrate potential for selective multi-metal recovery when processing dusts with elevated copper, lead, or nickel content.

Hybrid pyro-hydrometallurgical combinations represent the emerging technological frontier, combining pyrometallurgical phase destruction of refractory zinc ferrite with hydrometallurgical metal selectivity to achieve >95% comprehensive recovery. Implementation barriers remain primarily economic and regulatory rather than technical, reflecting the current industrial dominance of established Waelz technology and limited environmental enforcement regarding dust valorization in some regions.

Future development priorities should emphasize: (1) process integration enabling reagent and heat recycling to reduce operational energy; (2) life cycle assessment frameworks standardizing environmental comparison across technologies; (3) regulatory harmonization encouraging secondary resource recovery in emerging economies; and (4) continued mechanistic research on zinc ferrite reduction and selective metal extraction under mild conditions. The transition toward circular economy principles in metallurgical industries will progressively increase dust recovery from current 40-50% recovery rates toward >90% targets, substantially reducing both mining-related environmental impacts and primary metal production energy demands.

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