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ROTAS NÃO HIDROMETALÚRGICAS PARA O TRATAMENTO DO PÓ DE ACIARIA (EAFD): UMA REVISÃO CRÍTICA

ALTERNATIVE NON-HYDROMETALLURGICAL ROUTES FOR ELECTRIC ARC FURNACE DUST (EAFD) TREATMENT: A CRITICAL REVIEW

Antonio Clareti Pereira*
Doutor em Engenharia Química
Universidade Federal de Minas Gerais – UFMG - Engenharia Química
Belo Horizonte – MG - Brasil
E-mail: claretipereira@gmail.com

José Rubens dos Santos
Graduado em Engenharia Química
Universidade Presbiteriana Mackenzie - São Paulo – SP - Brasil
E-mail: eng_engenharia2@hotmail.com

Jussara Vanessa Freitas da Silva
Especialista em Engenharia Ambiental
Universidade Federal de Minas Gerais -UFMG- Engenharia de Minas
Belo Horizonte – MG - Brasil
E-mail: jussarafreitas2025@gmail.com

*Autor correspondente: claretipereira@gmail.com

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Resumo

O pó de aciaria elétrica (EAFD) é um resíduo perigoso gerado no processo de fabricação de aço em fornos a arco elétrico, caracterizado por sua complexa composição química e elevado teor de metais pesados, como zinco, chumbo e ferro. Esta revisão tem como objetivo analisar criticamente as principais rotas de tratamento não hidrometalúrgicas aplicadas ao EAFD, com ênfase em processos pirometalúrgicos, tratamentos térmicos e físicos, bem como abordagens baseadas em imobilização, como a estabilização/solidificação (S/S). São apresentados fluxogramas ilustrativos, tabelas comparativas e análises de desempenho técnico, ambiental e econômico para cada rota avaliada. Além disso, o estudo destaca

aplicações emergentes do EAFD na indústria de materiais de construção, como insumo em cimentos e cerâmicas sinterizadas. As lacunas de pesquisa e perspectivas futuras são discutidas com foco na viabilidade industrial e na sustentabilidade ambiental dos processos. A revisão contribui com uma visão abrangente das alternativas tecnológicas para o aproveitamento ou descarte seguro do EAFD, priorizando soluções alinhadas à economia circular.
Palavras-chave: EAFD, pó de aciaria, rotas pirometalúrgicas, estabilização, reutilização industrial.

Abstract

Electric arc furnace dust (EAFD) is a hazardous by-product from steel production in electric arc furnaces, characterized by a complex chemical composition and high concentrations of heavy metals such as zinc, lead, and iron. This review aims to critically evaluate the main non-hydrometallurgical treatment routes applied to EAFD, focusing on pyrometallurgical processes, thermal and physical treatments, and immobilization strategies such as stabilization/solidification (S/S). Illustrative flowcharts, comparative tables, and technical, environmental, and economic performance assessments are provided for each approach. The study also highlights emerging applications of EAFD in the construction materials industry, including its use in cement and sintered ceramics. Research gaps and future perspectives are discussed in light of industrial feasibility and environmental sustainability. This review offers a comprehensive overview of technological alternatives for the recovery or safe disposal of EAFD, prioritizing solutions aligned with the circular economy.
Keywords: EAFD, steelmaking dust, pyrometallurgical routes, stabilization, industrial reuse.

1. Introduction

Electric Arc Furnace Dust (EAFD) is a hazardous solid waste generated during the steelmaking process, particularly from electric arc furnaces used in scrap-based steel production. Classified as hazardous due to its high content of heavy metals such as zinc (Zn), lead (Pb), cadmium (Cd), and chromium (Cr), EAFD poses significant environmental and regulatory challenges if improperly managed

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(YU, Y *et al*., 2024). At the same time, it represents a secondary source of valuable metals, especially zinc and iron, prompting increasing interest in recovery and recycling technologies (GRUDINSKY et al., 2024).

Traditionally, hydrometallurgical methods have been extensively studied and applied to extract zinc and other metals from EAFD, offering high recovery efficiencies under controlled conditions. However, these methods often generate large volumes of wastewater, require intensive chemical consumption, and present difficulties in treating complex mineral phases such as zinc ferrite ($ZnFe_2O_4$), which is highly refractory (YU, Y *et al*., 2024). Consequently, there is a growing need to explore and critically assess **non-hydrometallurgical** approaches that offer technically viable and environmentally sustainable alternatives.

Non-hydrometallurgical strategies include pyrometallurgical, thermal, physical, and solidification/stabilization (S/S) techniques. These routes focus either on recovering metals via high-temperature processes or on rendering EAFD inert through encapsulation in cementitious or ceramic matrices. Pyrometallurgical processes such as the Waelz kiln, rotary hearth furnace (RHF), and plasma arc smelting are already applied at industrial scales but remain energy-intensive and capital-demanding (GRUDINSKY et al., 2024). In contrast, S/S methods aim to immobilize toxic elements, enabling the safe disposal or reuse of EAFD in construction materials.

This review aims to provide a critical assessment of non-hydrometallurgical routes for EAFD processing, with emphasis on their technical performance, environmental implications, and economic feasibility. By consolidating recent advances and identifying research gaps, this article seeks to support the development of integrated and sustainable solutions for EAFD valorization aligned with circular economy principles.

1.1. General objectives

This review aims to provide a comprehensive and critical overview of non-hydrometallurgical processing routes for electric arc furnace dust (EAFD). The focus is on identifying and analyzing pyrometallurgical, thermal, physical, and stabilization/solidification (S/S) technologies that offer environmentally and economically viable alternatives to conventional hydrometallurgical methods.

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Specifically, the objectives of this article are:

- To describe the physicochemical characteristics of EAFD that influence its processing behavior.
- To review the current state of industrial and experimental non-hydrometallurgical techniques for EAFD treatment.
- To compare these techniques in terms of metal recovery efficiency, environmental performance, technical feasibility, and cost implications;
- To highlight knowledge gaps, technical barriers, and opportunities for process integration and optimization.
- To support future research and industrial initiatives focused on waste valorization and circular economy in the steel sector.

To fulfill the proposed objectives, a critical and selective literature search was conducted covering the period from 2003 to 2025. The databases consulted included **Scopus**, **ScienceDirect**, **SpringerLink**, **Web of Science**, and **Google Scholar**. Keywords used in various combinations were *"Electric Arc Furnace Dust", "EAFD", "pyrometallurgical treatment", "stabilization/solidification", "cementitious recycling", "plasma arc", "Waelz process", "RHF"*, and *"zinc recovery from steel dust"*. Peer-reviewed journal articles, technical reports, and book chapters were selected based on their relevance to **non-hydrometallurgical** treatment routes for EAFD, with a focus on technical, environmental, and economic aspects. Studies dealing exclusively with hydrometallurgical methods or lacking substantial data were excluded from this review.

2. Review of literature

2.1. Physicochemical Properties Of EAFD

Electric arc furnace dust (EAFD) is a complex particulate material composed primarily of oxides and ferrites of zinc, iron, lead, and other trace metals. Its generation is associated with the volatilization and subsequent condensation of metal vapors during steelmaking operations, particularly in processes that involve scrap recycling (BADEA *et a*l., 2024; XU et al, 2023; PARSONS; SEAL II, 2015).

The chemical composition of EAFD varies depending on raw materials and process conditions but generally includes zinc oxide (ZnO), zinc ferrite ($ZnFe_2O_4$), magnetite (Fe_3O_4), hematite (Fe_2O_3), lead oxide (PbO), and lime (CaO), among

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other constituents (YU, Y *et al*., 2024; KIRANKUMAR et al, 2022; HECK; VILELA, 2017).

Table 1 presents the typical chemical composition of EAFD, highlighting its high contents of zinc and iron oxides, along with significant levels of lead, chromium, and chlorides. Zinc is primarily present as ZnO and zinc ferrite ($ZnFe_2O_4$), while iron appears mostly as Fe_3O_4 and Fe_2O_3 (GRUDINSKY et al., 2024). The presence of toxic metals such as Pb, Cd, and Cr, as well as water-soluble species like Cl^-, reinforces the hazardous classification of EAFD according to environmental regulations (YU, Y *et al*., 2024).

Table 1: Typical Chemical Composition of Electric Arc Furnace Dust (EAFD)

Component	***Range (% w/w)***
ZnO	*5–40*
Fe_2O_3	*15–50*
PbO	*0.1–5*
CaO	*1–15*
MgO	*0.5–5*
Cr_2O_3	*0.1–3*
CdO	*<0.1*
Cl^-	*1–10*

One of the most challenging features of EAFD is the presence of zinc ferrite ($ZnFe_2O_4$), a spinel-type structure that is chemically stable and poorly soluble in dilute acids, making it refractory to hydrometallurgical extraction. This mineralogical complexity directly influences the choice of treatment method and favors high-temperature routes capable of breaking these phases (GRUDINSKY et al., 2024; ZHANG et al., 2024).

From a physical perspective, EAFD is characterized by a fine particle size distribution, typically below 10 µm, and a high specific surface area, which enhances its reactivity but also poses challenges in handling, dust suppression, and occupational health risks (TRIFUNOVIĆ et al., 2022). The material often presents a gray to dark brown color, and its morphology consists of irregular and spherical particles formed by condensation in the off-gas system (BADEA *et a*l., 2024).

The mineralogy of EAFD, as revealed by XRD and SEM-EDS analyses in various studies, confirms the predominance of complex metal oxides and silicates, many of which are non-stoichiometric and metastable (ZHANG et al., 2024). This

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heterogeneity, combined with the presence of hazardous elements such as Pb and Cd, underscores the importance of choosing treatment strategies that ensure both metal recovery and environmental safety.

In summary, the physicochemical heterogeneity of EAFD dictates its behavior under different treatment conditions and strongly influences the selection of viable non-hydrometallurgical processing routes.

2.2. Pyrometallurgical Routes

2.2.1. Waelz Process

The Waelz process is the most widely adopted pyrometallurgical route for the treatment of EAF dust (EAFD), especially when zinc recovery is the primary objective. It involves the high-temperature reduction of zinc compounds present in the dust, typically at 1000–1200 °C, using a rotary kiln and a carbonaceous reductant, usually coke or coal. In this process, zinc oxides are reduced to metallic zinc, which is then volatilized and re-oxidized in the gas phase to form ZnO fume, later collected in bag filters (THOTEMPUDI et al, 2022).

The residual kiln product, known as Waelz slag, is a ferro-silicate material rich in Fe, Ca, Mn, and Mg, with low levels of zinc. However, it may still contain hazardous elements such as Pb and Cr, limiting its direct reuse unless subjected to stabilization or further treatment (ZHANG *et al.,* 2021).

Although the Waelz process allows recovery of up to 90% of zinc, its energy consumption is high, and it produces secondary emissions, such as CO_2 and chlorinated compounds from volatilized salts like $ZnCl_2$ (BAYOUMI et al., 2022). Moreover, the zinc ferrite phase ($ZnFe_2O_4$), which is thermodynamically stable and refractory, is only partially reduced under conventional Waelz conditions (XUE *et al*., 2023).

Despite these drawbacks, the Waelz process remains attractive due to its industrial maturity, compatibility with existing infrastructure, and ability to process large EAFD volumes. Various technological improvements, such as oxygen enrichment, pre-reduction, and slag recycling, have been explored to enhance efficiency and reduce environmental impacts (GRUDINSKY et al., 2024).

The Waelz process flow diagram (Erro! Fonte de referência não encontrada.) illustrates the main stages involved in the pyrometallurgical recovery

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of zinc and lead from EAF dust (EAFD). The process begins with the homogenization and drying of the EAFD, followed by its mixing with a solid carbonaceous reductant (usually coke breeze). This mixture is then fed into a rotary kiln operating at 1000–1200 °C, where ZnO and PbO are reduced to their metallic forms.

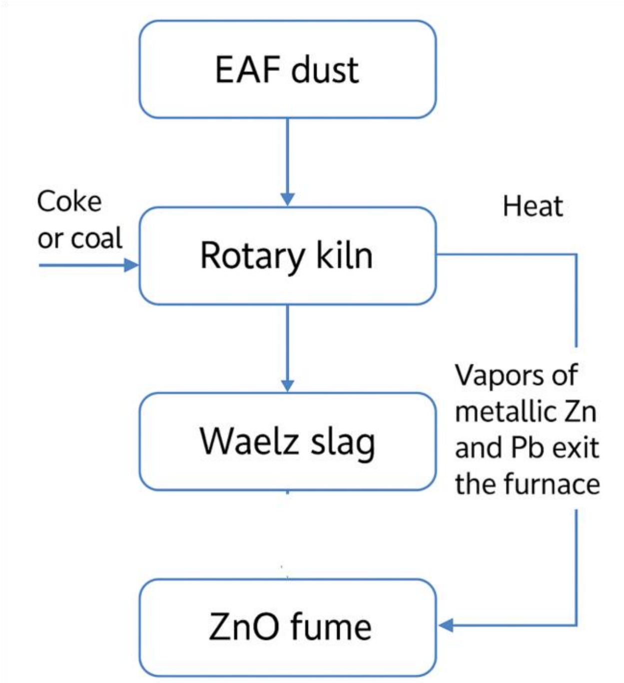

Figure 1: Waelz Process

The generated metallic vapors of Zn and Pb exit the kiln with the hot gas stream and are re-oxidized in the gas phase to form ZnO and PbO fume, which is captured in baghouse filters. The residual solid, known as Waelz slag, is discharged from the kiln and contains Fe, Ca, Mn, Mg, and small amounts of unrecovered metals.

This flow highlights the key thermochemical transformations and material separation occurring during the Waelz process, which allows for the selective volatilization of zinc and lead compounds, while other elements remain in the slag. However, the presence of refractory zinc ferrite ($ZnFe_2O_4$) limits complete Zn recovery unless the process is optimized (XUE *et al*., 2023).

The Waelz process is considered robust and scalable, but its drawbacks include high energy consumption, formation of secondary emissions, and the necessity to manage hazardous Waelz slag (ZHANG *et al.,* 2021; BAYOUMI et al., 2022). Despite these limitations, it remains the leading industrial technology for

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EAFD valorization due to its operational maturity and industrial integration potential (GRUDINSKY et al., 2024).

2.2.2. Reducing Hearth Furnace (RHF)

The Reducing Hearth Furnace (RHF) is a pyrometallurgical process developed as an alternative to the Waelz process for the treatment of electric arc furnace dust (EAFD), particularly in integrated steel plants. In the RHF process, pelletized EAF dust is mixed with a carbonaceous reductant and heated in a rotary or stationary furnace with a reducing atmosphere, typically at 1250–1350 °C.

During the process, metal oxides such as ZnO and Fe_3O_4 are reduced to metallic Zn (in vapor form) and elemental iron. Zinc vapor is oxidized and recovered as ZnO fume, while iron remains in the reduced pellet, forming a direct reduced iron (DRI)-like product. This residue, rich in Fe, can be recycled into steelmaking, improving material circularity (HANSEN et al., 2020).

Unlike the Waelz process, RHF operates with solid-state reduction in thin layers or pellets, allowing better control of reduction kinetics and minimizing slag generation. In addition, RHF offers lower specific energy consumption and potential integration with heat recovery systems (KONDO et al., 2015).

However, the RHF process requires strict control of pellet size, temperature profile, and residence time to ensure complete zinc volatilization and iron metallization. Also, high carbon content and fine particle size of EAFD may cause agglomeration or sintering issues during heating (WANG *et al*., 2021).

Despite these challenges, the RHF process has been successfully applied in pilot and industrial scales in countries like China, Korea, and Japan, particularly when there is local demand for iron-rich residues and regulatory pressure for hazardous waste minimization (LIU et al., 2022).

Figure 2 presents a schematic flow diagram of the Reducing Hearth Furnace (RHF) process, used for the pyrometallurgical treatment of Electric Arc Furnace Dust (EAFD). In this route, the dust is first blended with a solid reductant, typically coal, and formed into pellets. These pellets are dried and then fed into a furnace operating under a reducing atmosphere at temperatures around 1250–1350 °C. During heating, metal oxides—particularly ZnO, PbO, and Fe_3O_4—undergo reduction, and volatile metals such as Zn and Pb are vaporized, reoxidized, and collected as fine oxides in the off-gas system. The solid residue,

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enriched in metallic Fe, may be recycled into steelmaking processes.

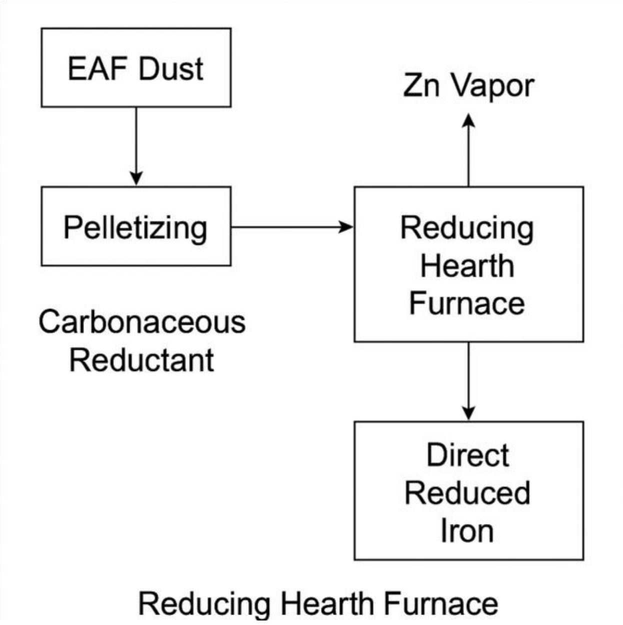

Figure 2: RHF Process

The RHF process stands out for its low slag generation, enhanced recovery of metallic Fe, and lower specific energy consumption compared to conventional processes like the Waelz process. The use of fine pellets enables better thermal uniformity and redox control, improving reaction efficiency (KONDO et al., 2015; LIU et al., 2022). However, success depends on strict control of pellet size, homogeneous mixture preparation, and precise furnace temperature profiling to prevent premature sintering and ensure metal volatilization (WANG *et al*., 2021).
Despite its technical advantages, large-scale adoption of the RHF process is limited by capital investment requirements, integration challenges with existing infrastructure, and the need for a stable market for the metallic Fe product (HANSEN et al., 2020).

2.2.3. Plasma Arc and Electric Smelting

Plasma arc and electric smelting technologies represent high-intensity pyrometallurgical routes for processing electric arc furnace dust (EAFD), enabling the recovery of valuable metals and the conversion of hazardous waste into inert slag. These processes operate at extremely high temperatures (above 1600 °C), using a plasma torch or electric resistance to generate a thermal environment suitable for the decomposition of complex oxides and the volatilization of Zn, Pb, and Cd, which are later captured in gas treatment systems (CHERRAT et al., 2025).

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In plasma arc furnaces, EAFD is typically mixed with a carbonaceous reductant and continuously fed into the plasma zone, where the intense heat promotes rapid melting and metal reduction. Zinc and other volatile metals evaporate and are oxidized in the off-gas line, while the non-volatile components—mainly iron oxides and silicates—form a molten slag phase that is periodically tapped (PEREIRA *et al*, 2025). Electric smelting follows a similar principle but uses submerged arc technology or resistive heating in a closed furnace chamber.

These technologies exhibit several key advantages:

- High metal recovery rates, particularly for Zn (>95%);
- Complete destruction of organic contaminants;
- Production of non-leachable vitrified slag suitable for construction applications.

However, the main limitations are the high capital and operating costs, the need for significant energy input, and the complexity of furnace design and gas treatment systems. Moreover, the availability of plasma torches and proper cooling systems restricts application in many industrial contexts (MENAD et al., 2021).

Despite these challenges, plasma-based technologies are gaining renewed attention due to their potential integration with renewable electricity and their ability to handle mixed or highly variable feedstocks, including EAFD, galvanized steel scrap residues, and other zinc-bearing wastes (NOWIŃSKA et al., 2023).

Figure 3 illustrates a schematic overview of the plasma arc and electric smelting process applied to EAF dust. The feed, composed of EAFD and reductant (typically carbon), is introduced into a high-temperature furnace where metals such as Zn, Pb, and Cd are volatilized. The remaining oxides form an inert slag, which is tapped and cooled. The volatilized metals are oxidized and captured in a gas treatment system.

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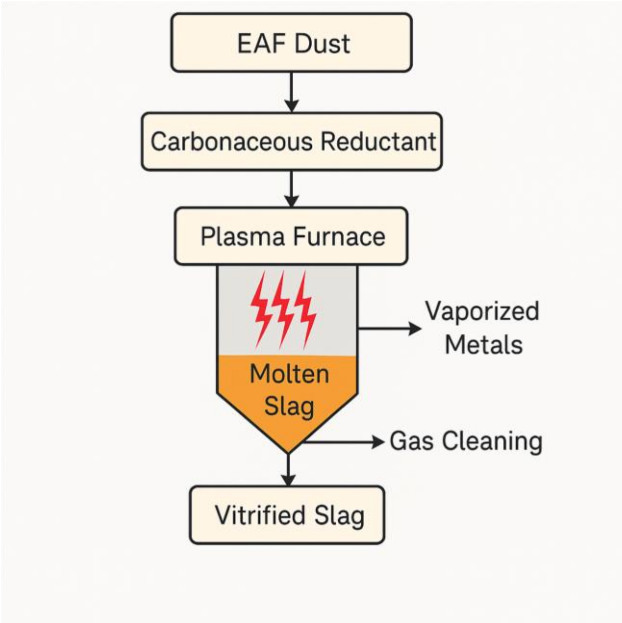

Figure 3:Plasma Process

This technology enables high zinc recovery yields (>95%), with the added benefit of generating a vitrified, non-leachable slag suitable for construction use (CHERRAT et al., 2025). It is especially effective for complex or contaminated feedstocks. However, the energy demand and investment costs are considerably higher compared to other pyrometallurgical options, which may limit broader industrial application (PEREIRA *et al*, 2025; NOWIŃSKA et al., 2023).

2.3. Physical and Thermal Treatment

2.3.1. Calcination

Calcination is a thermal treatment process typically carried out at temperatures ranging from 400 °C to 900 °C in oxidizing atmospheres. For electric arc furnace dust (EAFD), calcination serves as a pre-treatment method aimed at transforming or decomposing certain phases (e.g., carbonates, hydroxides) and stabilizing heavy metals in less soluble forms (KHEBRI et al., 2025).

In many cases, calcination is applied to reduce the reactivity and leachability of hazardous elements such as lead and cadmium. It also promotes the partial decomposition of zinc ferrite ($ZnFe_2O_4$) and increases the brittleness of EAFD particles, enhancing their amenability to further mechanical separation (GRUDINSKY, P, *et al* 2022). However, it is generally ineffective for complete metal recovery without subsequent chemical or physical steps.

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From a technological perspective, calcination can be performed in rotary kilns or shaft furnaces and often requires temperature control to avoid sintering of particles, which would otherwise reduce surface area and limit reactivity in subsequent processes (SHALABY *et al*., 2025). The formation of spinel-type phases, although contributing to stability, may also hinder subsequent extraction in integrated flowsheets.

While the process is relatively simple and scalable, the energy consumption and partial volatilization of metals at higher temperatures must be carefully controlled. Furthermore, calcination alone is not considered sufficient for EAFD detoxification but can be used as a preliminary treatment before vitrification, solidification, or magnetic separation (ABADI et al., 2024).

Figure 4 illustrates a simplified representation of the calcination process for electric arc furnace dust (EAFD). This thermal treatment involves feeding the dust into a rotary kiln or similar reactor, where it is subjected to controlled heating in an oxidizing atmosphere. Volatile components such as moisture and certain heavy metals may partially evaporate, while non-volatile phases undergo decomposition and structural transformation.

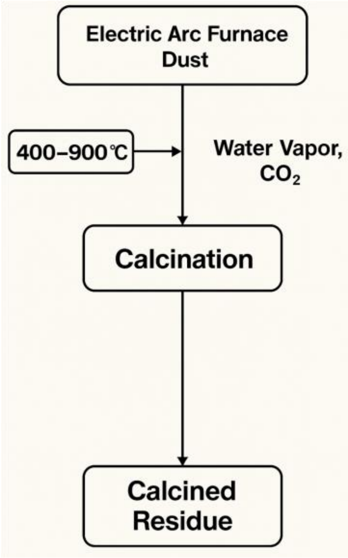

Figure 4: Calcination process

Calcination aims to reduce the leachability of hazardous elements and improve the physical properties of EAFD, facilitating downstream treatment. However, the energy demand, risk of sintering, and formation of stable spinel

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phases limit its efficiency as a standalone detoxification method (SHALABY *et al*., 2025; ABADI et al., 2024).

2.3.2. Magnetic Separation

Magnetic separation is a widely applied physical treatment used to fractionate electric arc furnace dust (EAFD) into magnetic and non-magnetic components. The process generally employs drum or belt magnetic separators to isolate ferromagnetic iron-rich phases, primarily magnetite (Fe_3O_4) and metallic Fe, from the remaining zinc- and lead-bearing oxides (PEREIRA *et al*, 2025; LIU et al., 2023).

This method enables the partial recovery of iron units for recycling within the steelmaking process, thereby reducing waste generation and raw material demand. However, non-magnetic fractions still retain hazardous compounds and require further stabilization or treatment. Magnetic separation alone is insufficient to detoxify EAFD, but it plays a valuable role as a preliminary step before pyrometallurgical or stabilization routes (PEREIRA *et al*, 2025; DERLON et al., 2022).

Figure 5 illustrates a schematic flowchart of the magnetic separation process applied to EAFD. In this route, raw EAFD is fed into a magnetic separator, which splits the stream into two fractions: a magnetic concentrate rich in iron oxides (mainly Fe_3O_4 and metallic Fe), and a non-magnetic residue containing zinc, lead, and other hazardous compounds.

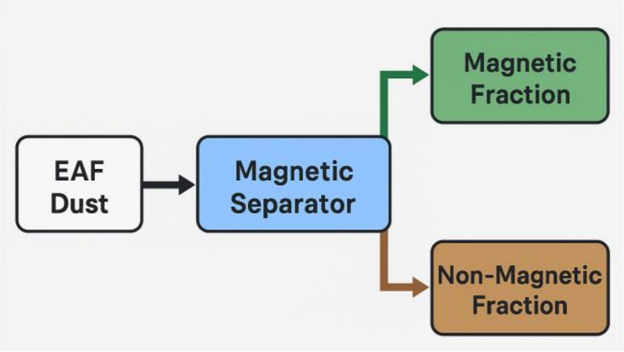

Figure 5: Magnetic Separation.

Magnetic separation is a relatively simple and low-cost method that allows partial recovery of iron for recycling in steelmaking. However, its effectiveness is limited to ferromagnetic components, and the non-magnetic fraction still requires further treatment or stabilization due to its environmental risk. Therefore, this

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technique is best employed as a preliminary step integrated into broader recovery or stabilization processes (PEREIRA *et al*, 2025; DERLON et al., 2022).

2.3.3. Mechanochemical Activation (Activated Grinding)

Mechanochemical activation, often referred to as activated grinding, is a physical treatment that enhances the reactivity of inert or low-reactivity solid waste materials, such as electric arc furnace dust (EAFD), by applying high-energy mechanical forces. In this process, EAFD is subjected to intensive grinding in planetary mills or attritors, generating structural defects, increasing surface area, and inducing partial amorphization (GÜLCAN *et al*., 2024; BALÁŽ , 2021).

The main advantage of mechanochemical activation is its potential to destabilize stable compounds like zinc ferrite ($ZnFe_2O_4$), enhancing subsequent extraction or stabilization processes. It can also contribute to particle size reduction, facilitating mixing with additives or binders in cementitious applications. However, the technique demands significant energy input and often requires further steps for complete detoxification or valorization of the treated dust (ZHANG *et al*, 2022).

Figure 6 presents a schematic representation of the mechanochemical activation process applied to Electric Arc Furnace Dust (EAFD). In this process, the material undergoes high-energy grinding, leading to structural disorder, increased surface area, and partial amorphization. These transformations enhance the chemical reactivity of inert phases such as zinc ferrite, facilitating further processing or stabilization.

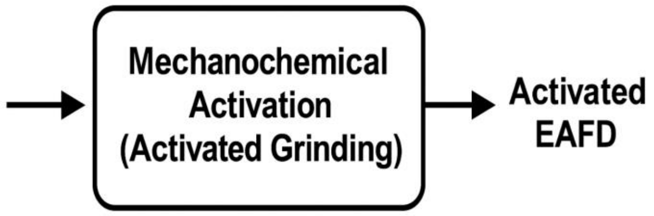

Figure 6: Activated Grinding.

Mechanochemical activation has emerged as a promising pretreatment route due to its low chemical input and ability to convert refractory compounds into more reactive forms. However, the energy-intensive nature of the grinding process and the need for additional treatment steps remain limitations for its large-scale

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implementation (PEREIRA *et al*, 2025; BALÁŽ, 2021; ALPA, 2012; ZHANG *et al*, 2022).

2.4. Cementitious and Ceramic Applications.

2.4.1. In Portland Cement

Electric Arc Furnace Dust (EAFD) has been extensively investigated as a partial substitute in Portland cement formulations, aiming at sustainable waste valorization and reduction of clinker content. The incorporation of EAFD into cement matrices typically ranges from 1% to 15% by weight, depending on chemical composition and processing conditions.

The main benefits observed include reduced demand for natural raw materials, enhanced immobilization of heavy metals through hydration reactions, and potential contribution of iron oxides as a fluxing agent during clinker formation. However, the presence of zinc, lead, and other volatile elements may delay cement hydration or reduce compressive strength when used in excess (DURIN et al., 2015; TEKİN et al., 2013).

To ensure environmental and mechanical performance, pre-treatment steps such as calcination, stabilization, or grinding are often recommended prior to cement incorporation. When properly processed, EAFD-containing cement can meet the technical standards for construction use and simultaneously reduce landfill disposal.

Table 2 summarizes selected studies that investigated the incorporation of Electric Arc Furnace Dust (EAFD) in Portland cement production. The use of EAFD as a partial substitute for clinker or as a mineral additive has shown potential to reduce environmental impacts and raw material consumption.

Table 2: Effects of EAFD Incorporation in Portland Cement

Evaluated Parameter	Effect of EAFD Addition	Technical Observations
Compressive strength	May decrease at high ratios (>10%)	Zn and Pb interfere with C_3S and C_3A hydration (TEKİN et al., 2013)
Dimensional stability	Generally stable up to 5–10% EAFD	Depends on thermal or chemical pre-treatment (DURIN et al., 2015)

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Evaluated Parameter	Effect of EAFD Addition	Technical Observations
Cement hydration	Slightly delayed	Zinc presence inhibits C-S-H nucleation
Heavy metal retention	High retention in cementitious matrix	Immobilization improves over curing time (TAY et al., 2001)
Raw material substitution	Partial replacement of Fe_2O_3 possible	Reduces the need for iron ore in clinker production
Environmental impact	Reduced hazardous waste disposal	As long as leaching levels comply with regulatory limits (ABNT NBR 10004)

Laboratory-scale studies indicate that low additions of EAFD (typically below 5–10 wt.%) can be safely incorporated without compromising the mechanical strength or setting time of cementitious products. Moreover, the presence of iron oxides and zinc compounds may contribute to the hydraulic activity and densification of the matrix. However, concerns remain regarding the leaching of heavy metals and long-term durability, especially when higher EAFD contents are used (DURIN; PEREIRA; OLIVEIRA, 2015; TEKİN; YILMAZ; KAZANCIOĞLU, 2013).

Further optimization of mixed design and sintering conditions is required to balance performance, safety, and environmental compliance.

2.4.2. Sintered Ceramics

The use of Electric Arc Furnace Dust (EAFD) as a raw material in the production of sintered ceramics represents an effective strategy for the stabilization of heavy metals and the valorization of industrial waste. EAFD typically contains high levels of iron, zinc, and other oxides that can participate in the ceramic matrix formation, especially in compositions with clay, feldspar, or glass waste.

Studies have shown that the incorporation of EAFD in ceramic formulations—up to 20 wt.%—can promote vitrification, reduce porosity, and improve densification when sintered between 1000 and 1150 °C (GUARINO; ULGIATI; MONTORSI, 2019; CHENG; LEE; LIN, 2011). Zinc and lead, often present in EAFD, tend to become encapsulated in glassy or spinel-like phases, reducing leachability and ensuring environmental safety.

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However, excessive addition of EAFD may impair color, mechanical resistance, or increase the volatilization of metal species during firing. Therefore, optimal incorporation rates and careful control of firing atmosphere are essential to ensure both performance and environmental compliance (LAVOURA; GARCIA; DALL'AGNOL, 2013).

Table 3 summarizes selected studies on the use of Electric Arc Furnace Dust (EAFD) in the production of sintered ceramics. The addition of EAFD, typically between 5–20 wt.%, was tested at sintering temperatures ranging from 950°C to 1150°C. The outcomes indicate promising pathways for EAFD valorization:

- **Cheng et al. (2011)** reported enhanced densification and efficient encapsulation of zinc in the ceramic matrix.
- **Guarino et al. (2019)** highlighted the environmental benefits and formation of stable ceramic phases, reducing leaching potential.
- **Lavoura et al. (2013)** achieved ceramics with low water absorption and improved chemical stability.

Table 3: Summary of sintered ceramics produced with EAFD additions

Study	EAFD Content (wt.%)	Sintering Temp. (°C)	Key Observations
Cheng et al. (2011)	5–20	1000–1100	Improved densification; Zn encapsulated
Guarino et al. (2019)	5–15	1000–1150	Environmental benefits; stable ceramic phase
Lavoura et al. (2013)	10–20	950–1050	Low water absorption; reduced leaching

These findings demonstrate that sintered ceramics represent a feasible and sustainable alternative for EAFD reuse, minimizing environmental liabilities and contributing to circular economy strategies.

2.5. Stabilization/Solidification (S/S)

Stabilization/solidification (S/S) is a well-established technique for treating hazardous industrial residues such as Electric Arc Furnace Dust (EAFD), aiming primarily at immobilizing heavy metals rather than recovering valuable elements. In

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this process, EAFD is mixed with binders—typically Portland cement, lime, fly ash, or pozzolanic materials—to form a stable solid matrix that reduces the leaching of hazardous components (SHI, X et al., 2025).

The stabilization mechanism involves both chemical fixation, where metal species react with hydroxides, carbonates, or silicates, and physical encapsulation, where EAFD particles are trapped within the hardened cementitious matrix (SABZI *et al*, 2021). Laboratory leaching tests, such as TCLP and EN 12457, often show significant reductions in leachable Zn, Pb, and Cd after S/S treatment (RASHAD, et al., 2021).

However, S/S does not reduce the total metal content, and potential long-term durability issues, such as carbonation or sulfate attack, may affect the immobilization efficiency over decades. Moreover, high EAFD content (>20 wt.%) can impair mechanical strength due to the formation of expansive phases like zinc hydroxide, which interferes with cement hydration (CIFRIAN *et al*., 2021; SHI, X et al., 2025).

Despite these limitations, S/S remains a cost-effective and widely implemented option for landfill disposal compliance and is also used to produce construction materials with acceptable environmental performance.

Table 4 summarizes the most common binders employed in the solidification/stabilization (S/S) of electric arc furnace dust (EAFD), focusing on their mechanisms of action, mechanical performance, and efficiency in reducing heavy metal leaching. Traditional binders such as Portland cement and lime promote metal immobilization primarily through pH control and precipitation of hydroxides. However, their effectiveness is often limited by interactions with heavy metals like Zn and Pb, which may interfere with the hydration process (SHI, X et al., 2025; CIFRIAN *et al*., 2021).

Table 4: Common Binders Used in S/S of EAFD and Their Performance

Binder	Typical EAFD Content (% wt.)	Main Reactions / Mechanisms	Compressive Strength (MPa)	Heavy Metal Leaching Reduction	Key Limitations	Reference
Portland Cement	5–20	Hydration, precipitation of metal	10–25	Moderate to high	Interference of Zn/Pb with hydration	SHI, X et al., (2025)

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Binder	Typical EAFD Content (% wt.)	Main Reactions / Mechanisms	Compressive Strength (MPa)	Heavy Metal Leaching Reduction	Key Limitations	Reference
		hydroxides				
Lime (CaO)	10–30	pH increase, metal hydroxide precipitation	<10	High (especially for Pb, Zn)	Low mechanical strength	CIFRIAN *et al.*, (2021)
Fly Ash	10–25	Pozzolanic reaction, physical encapsulation	5–15	Moderate	Requires activation or combination with cement	SABZI *et al*, (2021) (
GGBFS	5–15	Hydraulic reaction, ion exchange	15–30	High	Activation required (e.g., with NaOH or lime)	RASHA**D,** et al. (2021)
Magnesia (MgO)	10–20	Formation of stable metal hydroxides and carbonates	8–18	Moderate to high	Higher cost, slower setting time	CIFRIAN *et al.*, (2021)
Geopolymer Binder	10–30	Alkali-activation, formation of aluminosilicate networks	20–40	Very high	Requires controlled curing, alkaline activator handling	SHI, X et al., (2025); RASHAD, et al. (2021)

Supplementary materials such as fly ash and ground granulated blast furnace slag (GGBFS) offer pozzolanic and hydraulic reactions, enhancing matrix densification and immobilization. Nonetheless, their performance frequently depends on chemical activation (SABZI *et al*, 2021; RASHAD, et al., 2021). More recently, geopolymer binders have demonstrated superior compressive strength and leaching control, although they demand stringent curing conditions and careful handling of alkaline activators (SHI, X et al., 2025; RASHAD, et al., 2021). These findings reinforce the importance of tailoring the binder selection based on the chemical characteristics of the EAFD and the final application of the stabilized product.

2.6. Environmental and Economic Considerations

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The pyrometallurgical and stabilization/solidification (S/S) routes for electric arc furnace dust (EAFD) processing offer significant environmental advantages by minimizing hazardous waste landfilling and reducing long-term ecological liabilities. However, they vary widely in terms of energy consumption, CO_2 emissions, operational complexity, and costs. Pyrometallurgical processes such as the Waelz kiln and plasma arc systems typically require high energy inputs and generate secondary emissions (SHI, X et al., 2025). Nevertheless, their ability to recover valuable metals like Zn and Pb offers economic returns that may partially offset the operational costs (JHA; DUTTA, 2009).

In contrast, S/S techniques—especially those incorporating industrial by-products such as fly ash, slag, and geopolymers—present low-carbon alternatives with lower capital and operating expenditures. While they do not recover metals, they stabilize hazardous elements effectively, allowing the treated EAFD to be safely landfilled or reused in construction applications (**RASHAD,** et al., 2021; SABZI *et al*, 2021).

Cost-benefit analyses must consider the target product, regulatory framework, material availability, and local energy prices. In regions with stringent leaching regulations and high landfill costs, the S/S route may be preferable. Conversely, in metallurgically integrated plants, metal recovery via thermal routes may offer better economic returns. Lifecycle assessment and techno-economic analysis remain critical tools in selecting the optimal treatment strategy for EAFD.

Table 5 provides a comparative overview of the main environmental aspects associated with different treatment routes for electric arc furnace dust (EAFD). Pyrometallurgical processes such as the Waelz kiln, rotary hearth furnace (RHF), and plasma arc smelting are characterized by high energy demand and substantial emissions of acid gases, metallic vapors, and dust particles, requiring efficient gas cleaning systems and energy input (XUE *et al*., 2023; XIAO et al., 2021; RAMEZANI MOZIRAJI et al., 2023).

Table 5: Environmental Aspects of EAFD Treatment Routes

Treatment Route	Energy Demand	Environmental Impact	By-Products / Residues
Waelz Process	High	Significant gas emissions (Cl_2, SO_2, Pb); dust generation	ZnO, Fe-rich slag
RHF Furnace	Very High	CO_2 and SOx emissions; coke	DRI (Zn-free), Zn/Pb

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Treatment Route	Energy Demand	Environmental Impact	By-Products / Residues
		usage; dioxin formation possible	fumes, slag
Plasma Arc Furnace	Very High	Reduced emissions; efficient gas treatment at high temperature	Inert slag, Zn/Pb fumes
Electric Arc Melting	Very High	Controlled atmosphere reduces emissions; slag and fume formation	Alloyed metal, slag, Zn vapor
Calcination	Moderate	Dust generation; thermal decomposition of carbonates and oxides	Desulfurized or oxidized residue
Magnetic Separation	Low	No direct emissions; may produce fine, airborne particulates	Fe-rich magnetic fraction; non-magnetic waste
Activated Grinding	Moderate	No emissions; noise and dust exposure during operation	Amorphized particles with higher reactivity
Cementitious Recycling	Low	Encapsulation of metals; minimal emissions if done dry	Cemented product with reduced mobility of metals
Sintered Ceramics	High	Volatilization of some metals during sintering; thermal energy demand	Dense ceramics, inertized metals
S/S with Inorganic Binders	Low to Medium	Immobilization reduces leaching; binder production has environmental cost	Solidified blocks with encapsulated contaminants
Geopolymer-based Stabilization	Medium	High pH leachates possible; requires handling of alkalis	Alkali-activated matrix with low metal mobility

In contrast, physical treatments such as magnetic separation and mechanochemical activation involve lower direct environmental impact but may pose operational risks related to fine particulate release (YU, Y *et al.*, 2024; GUO et al., 2020). Valorization routes, including incorporation into Portland cement, sintered ceramics, and solidification/stabilization (S/S), offer environmental benefits by immobilizing heavy metals and reducing the hazardous nature of EAFD. However, they may result in alkaline leachates or require high-temperature sintering steps, depending on the matrix and technology (SHI, X et al., 2025; BERNARDO et al., 2007).

Among these, geopolymer binders are particularly promising due to their high efficiency in metal retention and lower emission profile. Nevertheless, they require careful curing conditions and handling of alkaline activators (RASHAD, et al., 2021). As such, the selection of a suitable EAFD treatment route must balance environmental performance, technical feasibility, by-product management, and

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regulatory compliance.

Table 6 provides a comparative overview of the main environmental aspects associated with different treatment routes for electric arc furnace dust (EAFD). Pyrometallurgical processes such as the Waelz kiln, rotary hearth furnace (RHF), and plasma arc smelting are characterized by high energy demand and substantial emissions of acid gases, metallic vapors, and dust particles, requiring efficient gas cleaning systems and energy input (XUE *et al*., 2023; XIAO et al., 2021; RAMEZANI MOZIRAJI et al., 2023).

Table 6: Economic Aspects of EAFD Treatment Routes

Treatment Route	Estimated CAPEX	Estimated OPEX	Reference
Waelz Process	High	High	XUE *et al*., (2023); PICKLES (2010)
RHF Furnace	High	High	RAMEZANI MOZIRAJI et al. (2023)
Plasma Arc Furnace	Very High	High	XIAO et al. (2021); CIFRIAN *et al*., (2021)
Electric Arc Melting	High	High	KUL et al. (2015)
Calcination	Medium	Medium	SABZI *et al*, (2021)
Magnetic Separation	Low	Low	YU, Y *et al*., (2024); TOPORKOVA et al. (2020)
Activated Grinding	Low to Medium	Low	AL-HARBI et al. (2017); GUO et al. (2020)
Cementitious Recycling	Low	Low	SHI, X et al., (2025); CIFRIAN *et al*., (2021)
Sintered Ceramics	Medium	Medium	BERNARDO et al. (2007); GARCÍA-VALTIERRA et al. (2018)
S/S with Inorganic Binders	Low	Low	RAMEZANI MOZIRAJI et al. (2023); SABZI *et al*, (2021)
Geopolymer-based Stabilization	Medium	Low to Medium	SHI, X et al., (2025); **RASHAD,** et al. (2021)

2.7. Research Gaps and Future Perspectives

Despite the significant progress in the development of non-hydrometallurgical

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routes for EAFD processing, several research gaps and technical challenges persist, limiting their broader industrial implementation.

First, most studies on pyrometallurgical processes such as the Waelz kiln, RHF, and plasma arc are based on pilot-scale or laboratory-scale results. The extrapolation of these findings to full-scale continuous operations is not straightforward due to variability in dust composition, refractory degradation, and control of volatilized metals. Additionally, comprehensive life cycle assessments (LCAs) and techno-economic evaluations remain scarce, particularly in developing economies where steelmaking residues are often underregulated (XUE *et al.*, 2023; RAMEZANI MOZIRAJI et al., 2023).

In physical and thermal treatments like magnetic separation and calcination, efficiency is highly sensitive to EAFD granulometry and mineralogy. Further research is needed to standardize pre-treatment steps and understand how thermally induced phase transformations affect subsequent recovery or immobilization (GUO et al., 2020; XIAO et al., 2021).

The application of EAFD in cementitious and ceramic materials has demonstrated technical viability, yet concerns remain regarding long-term durability, heavy metal leaching under environmental exposure, and regulatory acceptance. Optimization of binder formulations and accelerated leaching tests simulating real-life scenarios are needed to ensure safe utilization (SHI, X et al., 2025; RASHAD, et al., 2021).

Emerging approaches such as geopolymerization and mechanochemical activation require further exploration of process kinetics, binder chemistry, and scalability. Furthermore, the potential integration of multiple routes (e.g., plasma treatment followed by cementitious reuse of the slag) remains underexplored and could enhance both material valorization and environmental performance.

From a policy perspective, harmonization of standards and incentives for secondary raw materials, especially in steel-producing countries, could drive the adoption of sustainable EAFD management practices.

In future work, emphasis should be placed on:

- Pilot-scale validation of physical and pyrometallurgical routes in diverse geographic contexts.
- Development of hybrid or integrated treatment flowsheets.

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- Creation of databases correlating EAFD composition to treatment performance.
- Assessment of carbon footprint and environmental trade-offs for each technology.

Such advancements will be essential to bridge the gap between research and industrial implementation, enabling circular economy solutions for steelmaking residues.

3. Final Considerations

Electric arc furnace dust (EAFD) is a complex industrial residue with a highly variable composition, typically enriched in heavy metals such as zinc, lead, iron, and cadmium. Due to its hazardous nature and valuable metal content, several technological approaches have been developed and optimized to promote its recycling or safe disposal.

Table 7: Comparative Overview of Non-Hydrometallurgical EAFD Treatment Routes

Treatment Route	Metal Recovery Potential	Environmental Impact	Process Complexity	Estimated CAPEX	Estimated OPEX
Waelz Process	High (Zn: up to 90%)	High emissions	High	High	High
RHF Furnace	**High (Zn, Fe)**	Moderate to high	High	High	High
Plasma Arc Smelting	Very High (>95% Zn)	Moderate	Very High	Very High	High
Calcination	Low to None	Moderate	Low	Medium	Medium
Magnetic Separation	Low (Fe only)	Low	Low	Low	Low
Activated Grinding	Indirect (enhances reactivity)	Low	Medium	Low to Medium	Low
Cementitious Recycling	None (immobilization)	Low	Low	Low	Low
Sintered Ceramics	None (immobilization)	Moderate	Medium	Medium	Medium
S/S with Cement/Lime	None (immobilization)	Low	Low	Low	Low
Geopolym	None	Low to	Medium	Medium	Low

Treatment Route	Metal Recovery Potential	Environmental Impact	Process Complexity	Estimated CAPEX	Estimated OPEX
er Stabilization	(immobilization)	Medium	to high		to Medium

Pyrometallurgical routes—such as the Waelz process, rotary hearth furnace (RHF), and plasma arc melting—have proven effective for recovering zinc and iron. However, these processes are associated with high energy consumption, substantial capital investment (CAPEX), and the generation of by-products that may still require environmental management. On the other hand, thermal and physical treatments—including calcination, activated grinding, and magnetic separation—enable pre-concentration or structural modification of EAFD, improving its potential for subsequent valorization.

Applications in Portland cement, sintered ceramics, and geopolymeric formulations offer sustainable routes for metal immobilization, facilitating the safe reuse of EAFD in the construction sector. Stabilization/solidification (S/S) techniques using various binders have shown high efficiency in reducing heavy metal leaching, though issues related to mechanical performance, durability, and industrial-scale feasibility still remain.

From both environmental and economic perspectives, the integration of technological strategies with circular economy policies is essential. Nevertheless, research gaps persist regarding detailed material characterization, reaction mechanisms, long-term performance of treated products, and process optimization.

In conclusion, the optimal route for EAFD treatment depends on multiple factors—including dust composition, available infrastructure, treatment costs, and environmental regulations. Continued interdisciplinary research and technological innovation will be crucial to enable environmentally sound and economically viable solutions for managing this critical by-product of the steelmaking industry.

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