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From Upgraded Titanium Slag to Modern Metallurgical Slag Engineering: Technologies, Industrial Applications, and Readiness-A Critical Review

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ABSTRACT: Metallurgical slags are increasingly treated as dynamic secondary resources rather than inert residues, yet the literature remains fragmented across metal recovery, mineral-phase engineering, material valorization, carbon management, and industrial implementation. This structured critical narrative review evaluates a recent core corpus of 111 publications from 2020–2026 and supplements it with selected pre-2020 foundational sources required to establish the historical Upgraded Slag (UGS) lineage in titanium metallurgy. The recent corpus was descriptively coded by primary slag family, evidence function, and implementation maturity; steelmaking/ferrous systems account for 60 studies, copper/fayalitic slags for 16, cross-cutting or mixed systems for 15, ferroalloy/Cr–Mn slags for 7, Ti-bearing slags for 4, and Ni/ferronickel slags for 3. Eighty publications primarily provide mechanistic or product-performance evidence, 13 provide system-assessment evidence, and 12 are reviews or contextual sources. The synthesis distinguishes historical titanium-slag upgrading from the broader family of modern thermal, chemical, redox, physical, hydrometallurgical, carbonation, and electrochemical interventions. It shows that credible upgrading requires more than high recovery: a controllable phase transformation must be coupled with effective separation, qualified metal or material products, a safe and useful residual matrix, and realistic integration with plant infrastructure. Representative industrial evidence is strongest in copper-slag flotation and settling, selected hot-stage steel-slag operations, and heat-recovery applications, whereas many high-value functional-material routes remain laboratory-led. A five-gate framework—value inventory, engineerability, separation and safety, integration, and system performance—is applied to representative routes to connect mechanisms with product specifications, TEA/LCA, and industrial readiness. The resulting perspective positions slag upgrading as site-specific product and process design within circular metallurgy rather than as generic residue reuse.

KEYWORDS: upgraded titanium slag, slag engineering, metal recovery, mineral phase modification, circular metallurgy, industrial readiness.

Highlights

- Historical UGS is distinguished from broader value-directed metallurgical slag engineering.
- The 111-publication recent corpus is mapped by slag family, evidence function, and readiness.
- Industrial evidence clusters in copper-slag treatment, selected hot-stage steel routes, and heat recovery.
- A five-gate framework links product quality, safety, integration, TEA/LCA, and industrial readiness.

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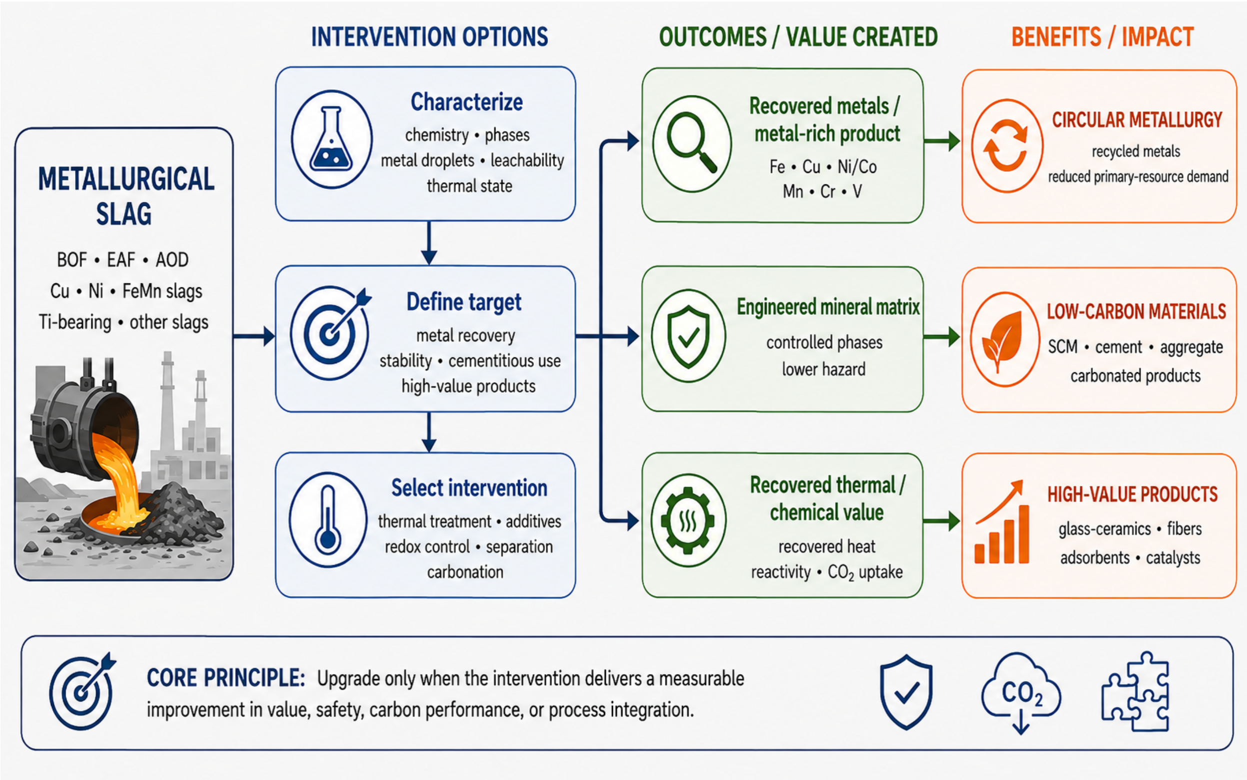
Graphical Abstract



1. INTRODUCTION

Metallurgical slag management is moving from an end-of-pipe waste problem toward a process-integration problem. Steelmaking, ferroalloy, copper, nickel, and titanium-bearing slags contain combinations of residual metal, oxides, latent heat, reactive calcium and magnesium phases, glass-forming constituents, and trace elements that can be either liabilities or resources depending on how the slag is cooled, conditioned, separated, and ultimately used. This shift is reinforced by circular-economy pressures in steelmaking, tightening carbon constraints, growing interest in secondary raw materials, and the practical need to reduce landfill while maintaining product quality and environmental compliance (Branca et al., 2020; Ehrenberg, 2025; Fan et al., 2025; Fan et al., 2026; Matsuura et al., 2022; Rieger et al., 2021; Sun et al., 2022; Voraberger et al., 2026; J. Yang et al., 2026).

Conventional utilization routes remain important, but they often capture only a fraction of the potential value. Granulation, crushing, aggregate use, and direct incorporation into construction products can be technically effective when the slag already meets the required chemistry and stability window. They become less satisfactory when valuable metal remains locked in the matrix, free CaO or MgO creates expansion risk, chromium or other trace elements remain mobile, or the thermal and chemical state of the slag is discarded before it can be exploited. Life-cycle and ex-ante assessments therefore increasingly compare not only disposal versus reuse, but also alternative treatment chains and their interaction with energy, emissions, market displacement, and plant infrastructure (Buyle et al., 2021; Duan et al., 2022; Li et al., 2024; Quéheille et al., 2021; J. Yang et al., 2026).

The term "upgrading" is useful only if it is more demanding than "reuse." In this review, an upgrading operation is defined as an intentional intervention that changes one or more controlling attributes of the slag—chemistry, phase assemblage, oxidation state, droplet or particle size, thermal content, porosity, surface reactivity, or contaminant binding—in order to create a product or intermediate with demonstrably higher technical, environmental, or economic value. This definition excludes simple relabelling of an untreated slag as a product and also distinguishes active engineering from passive aging or storage.

The historical Upgraded Slag (UGS) route is retained in this review as an industrially important precedent rather than as a generic label for all slag-treatment operations. In titanium metallurgy, upgrading deliberately transforms high-titania smelting slag into a feedstock with tighter impurity specifications. Modern slag engineering extends the same value-directed logic—characterize, transform, separate, and qualify—to steelmaking, copper, nickel, ferroalloy, and other metallurgical slags (Filippou & Hudon, 2020; Goso et al., 2022; Isaksson et al., 2023; Li et al., 2025; Liu et al., 2026).

Accordingly, this review has five objectives. First, it establishes the historical UGS lineage and clarifies its relationship to the broader field of slag engineering. Second, it describes a transparent, structured review methodology and maps the recent evidence base. Third, it critically compares thermal, chemical, redox, physical, hydrometallurgical, electrochemical, and reactive-conversion strategies. Fourth, it evaluates metal recovery, residual-matrix valorization, environmental performance, and plant integration together rather than as isolated endpoints. Fifth, it applies a five-gate industrial framework that links engineerability and product qualification to TEA/LCA and implementation readiness.

2. REVIEW METHODOLOGY, EVIDENCE BASE, AND SCOPE

2.1 Search strategy and corpus assembly

This article is a structured critical narrative review. The core recent evidence base comprises 111 publications issued from 2020 through 2026. The corpus was originally assembled through targeted Google Scholar retrieval and publisher/DOI verification using combinations of broad and slag-specific terms, including "slag upgrading," "metal recovery from metallurgical slag," "slag modification," "controlled cooling," "slag reduction," "hot-stage slag," "slag carbonation," "heat recovery from molten slag," and system-specific terms for electric arc furnace (EAF), basic oxygen furnace (BOF), copper, ferronickel, ferroalloy, and titanium-bearing slags. Because database hit counts and screening decisions were not prospectively archived when the corpus was first assembled, the review does not claim PRISMA completeness or fabricate a formal systematic review flow.

To address the historical meaning of UGS without changing the denominator used for the recent evidence map, selected pre-2020 foundational sources were added only for historical and mechanistic context. These sources document ilmenite-smelting chemistry, high-titania slag solidification, the mineralogy of upgraded titania slags, and the industrial patent lineage of oxidation–reduction–leaching upgrading. They are cited in the narrative but are excluded from all n = 111 descriptive corpus counts (Borowiec et al., 1998; Guéguin & Cardarelli, 2007; Pistorius & Coetzee, 2003; Zietsman & Pistorius, 2004).

2.2 Eligibility, screening, and evidence coding

For the revision, the curated recent corpus was audited using explicit retrospective eligibility rules. Sources were retained when they addressed metallurgical slag or closely coupled metallurgical residue and reported a transformation, separation, product performance, environmental, integration, or system assessment outcome relevant to upgrading. Duplicate records, studies unrelated to metallurgical slags, passive end uses lacking sufficient characterization, and sources without adequate technical information for critical comparison were outside the intended evidence base. Reviews, books, chapters, and contextual papers were retained only when they provided synthesis, historical framing, technology context, or industrial-system information not supplied by a single experimental study.

Each recent publication was assigned to a single primary slag-family category for descriptive counting. Multi-slag studies and cross-cutting analyses were assigned to "cross-cutting/other" to avoid double counting. A second, independent code classified evidence into function: primary mechanistic or product-performance evidence; system-assessment evidence (including TEA, LCA, feasibility, decision analysis, and industrial-system modeling); or review/contextual evidence. The resulting composition of the curated corpus is 60 steelmaking/ferrous studies, 16 copper/fayalitic studies, 15 cross-cutting/other studies, 7 ferroalloy/Cr–Mn studies, 4 Ti-bearing studies, and 3 Ni/ferronickel studies. By evidence function, 80 sources primarily provide mechanistic or product evidence, 13 provide system-assessment evidence, and 12 are review/contextual sources. These counts describe the composition of this curated review corpus; they should not be interpreted as a bibliometric census of the global literature.

Figure 1 is included here to make the imbalance in evidence explicit before technical comparisons are made. The map prevents a large body of steel-slag literature from being mistaken for indicating equivalent maturity across all slag families.

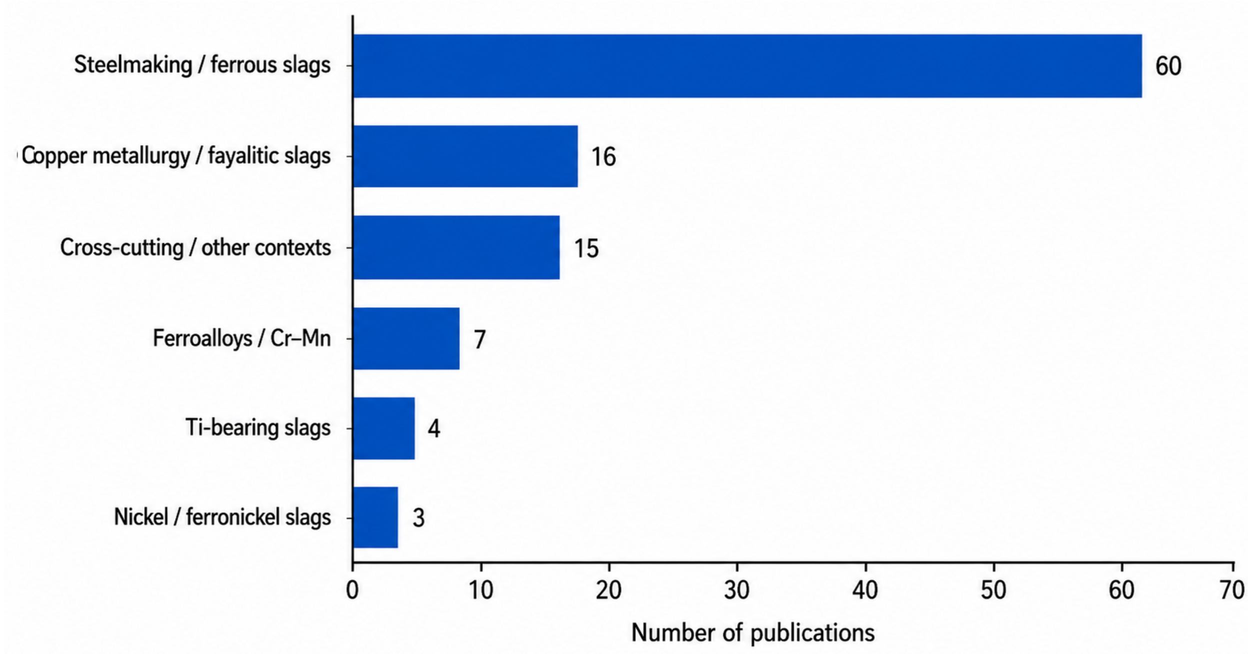


Figure 1. Distribution of the publication-recent corpus by primary slag family.

Note. Author-developed descriptive coding of the curated 2020–2026 corpus. Each source was assigned once to a primary slag family; cross-cutting and multi-slag sources were grouped separately. Foundational pre-2020 sources are excluded from the denominator.

The map shows that the evidence base is dominated by steelmaking/ferrous slags, while Ti-bearing and Ni/ferronickel systems are represented by much smaller recent clusters. This asymmetry is carried forward in the interpretation: strong statements about broad industrial readiness are restricted to pathways with plant-scale or industrially representative evidence, rather than generalized from the size of the overall literature.

2.3 Evidence maturity and industrial-readiness definitions

Implementation maturity was interpreted separately from evidence function. “Laboratory” refers to bench-scale batch, synthetic, model-slag, or controlled experimental work without plant-representative throughput. “Pilot” refers to integrated or semi-continuous operation with representative feed at a scale below production. “Demonstration/industrial trial” denotes operation with industrial material and/or plant equipment during a defined campaign, but without evidence of routine production. “Industrially demonstrated/operating” denotes repeated or continuous plant application or a documented industrial case. TEA, LCA, modeling, patents, and enabling process-control studies are treated as system evidence rather than being assigned a pseudo-TRL on their own. This distinction is important because unit-operation maturity and flowsheet maturity are not equivalent. Crushing, magnetic separation, flotation, leaching, or smelting may each be mature operations, while a novel sequence combining them with a specific phase-engineering step can remain low-readiness if feed variability, product qualification, residue safety, continuous control, or permitting have not been demonstrated.

2.4 Scope boundary and critical-comparison criteria

The term UGS is used only for the historically specific titanium-feedstock lineage. “Slag upgrading” and “slag engineering” denote the wider family of intentional interventions that change chemistry, phase assemblage, oxidation state, droplet or particle size, thermal content, porosity, surface reactivity, or contaminant binding to create a demonstrably higher-value product or intermediate. Simple relabeling of untreated slag, passive aging, and disposal avoidance without a specified product function are not treated as upgrading.

Five recurring criteria guide the critical comparison: transformation intensity; selectivity of the resulting phase or product separation; quality and safety of the residual matrix; integration potential with the primary metallurgical plant; and evidence maturity. These criteria are supplemented by quantitative performance data where studies are sufficiently comparable and by system-level TEA/LCA considerations where direct recovery metrics alone would be misleading.

2.5 Review limitations

The review has four principal limitations. First, the core corpus is curated rather than prospectively systematic, so publication and selection bias cannot be excluded. Second, slag compositions, feed grades, test methods, definitions of recovery, and system boundaries differ substantially; consequently, the review uses quantitative benchmarking only for representative cases and does not perform a meta-analysis. Third, industrial operating data are much less available than laboratory data and may be protected by commercial confidentiality. Fourth, the recent 2020–2026 window was chosen to emphasize current engineering directions; foundational pre-2020 sources are therefore used selectively for historical and mechanistic context rather than included in the descriptive evidence-map denominator.

3. SLAG FAMILIES, HISTORICAL UGS LINEAGE, AND UPGRADEABILITY

3.1 Historical UGS lineage: from high-titania slag to qualified feedstock

High-titania slags are produced by carbothermic smelting of ilmenite, where selective iron reduction yields a metallic iron phase and a Ti-rich oxide slag. Their behavior is controlled by multivalent titanium and iron, M3O5-type pseudobrookite solid solutions, impurity oxides, and solidification history; the resulting chemistry is therefore inseparable from furnace redox conditions and cooling (Pistorius & Coetzee, 2003; Zietsman & Pistorius, 2004). The UGS concept emerged from the need to convert such slags from intermediate smelting products into higher-grade titanium feedstocks rather than merely dispose of a residual oxide phase.

The industrial upgrading lineage uses deliberately sequenced phase transformation and selective impurity removal. A representative patent describes sizing followed by solid-state oxidation, reduction, mineral-acid leaching, washing and calcination, with optional caustic leaching for additional silica removal. The disclosed products typically contain about 94–96 wt.% TiO_2 while maintaining low CaO and MgO concentrations compatible with chloride-route requirements (Borowiec et al., 1998). Mineralogical reviews likewise show why oxidation/reduction pretreatment is essential: the objective is not simply dissolution, but conversion of impurity-bearing phases into a state that can be selectively leached while retaining the Ti-rich matrix (Guéguin & Cardarelli, 2007).

Recent modified-UGS work confirms both the durability and the limits of this logic. Goso et al. (2022) reported a product containing 90.5 mass% TiO_2 at 83% TiO_2 recovery from fluxed titaniferous slag. The TiO_2 grade met the targeted chloride-feedstock level, but several impurity and particle-size constraints remained. This result is instructive for the broader review: a high recovery or high target-element grade does not by itself define an upgraded product; downstream specifications remain decisive.

3.2 Steelmaking slags

The upgradeability of a slag is governed less by its nominal bulk chemistry than by the way that chemistry is distributed among phases, oxidation states, droplets, glass, and microstructural domains. Steelmaking slags illustrate this clearly. Basic oxygen furnace (BOF), electric arc furnace (EAF), argon oxygen decarburization (AOD), and ladle-furnace slags can contain free lime, periclase, calcium silicates, ferrites, spinels, metallic iron, and phosphorus- or chromium-bearing phases, but their proportions vary strongly with furnace practice, oxygen potential, cooling history, and secondary additions (Andersson et al., 2024; Andersson et al., 2026; Ashrit et al., 2020; Baras et al., 2023; Jacob, 2024; Menad et al., 2021; Xu et al., 2023). This variability explains why apparently similar slags can show very different expansion, leaching, magnetic-separation response, and cementitious reactivity.

3.3 Non-ferrous and specialty slags

Non-ferrous slags are equally heterogeneous. Copper slags are commonly iron-silicate-rich and may retain copper as matte or metallic droplets as well as dissolved or precipitated species. Nickel and ferronickel slags can be dominated by silicate phases but contain recoverable iron or nickel-bearing species. Ferroalloy slags may carry Mn, Cr, or other metals in oxide and spinel structures whose reducibility depends on activity, basicity, and temperature. Model-slag work and detailed characterization show that apparently small changes in composition or cooling history can alter viscosity, crystallization pathways, magnetic behavior, and the accessibility of valuable elements (Kero Andertun et al., 2021; Kim & Sohn, 2023; Kuanyshev et al., 2026; Vollbrecht et al., 2024; Wang, Tao, et al., 2021; Wang, Zeng, et al., 2021; Wang et al., 2020).

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3.4 Thermochemical state variables and purpose-specific characterization

Three state variables are especially important. The first is oxidation potential, which controls the valence states and mineral hosts of Fe, Cr, V, Mn, and other multivalent elements. The second is liquid structure and basicity, which affect viscosity, mass transfer, interfacial tension, modifier dissolution, and crystallization. The third is thermal history, which determines whether a slag becomes glassy, finely crystalline, coarse-crystalline, segregated, or phase-separated. These variables are coupled: changing basicity can alter liquid structure and crystallization; changing oxidation potential can affect both metal recovery and the phases remaining in the final residue.

A practical consequence is that slag characterization must be purpose-specific. Bulk XRF chemistry is necessary but not sufficient. Metal-recovery studies require information on metal occurrence, liberation, droplet size, magnetic response, and reducible oxide phases. Construction use requires free CaO/MgO, volume stability, hydraulic or pozzolanic reactivity, particle-size behavior, and leaching. Carbonation requires accessible Ca/Mg phases and transport pathways. Functional-material routes require control of glass network, active iron-bearing phases, or surface area. A single "slag composition" therefore cannot predict upgradeability without mineralogical and process context.

Because bulk chemistry alone does not determine upgradeability, Table 1 links the principal slag families to the state variables that govern their behavior and to the upgrading levers most likely to change those variables. The historical UGS route is included as the Ti-bearing reference case, while the remaining rows use the broader slag-engineering terminology.

Table 1. Metallurgical slag families, controlling state variables, and priority upgrading levers

Slag family	Controlling state variables	Main opportunities / liabilities	Priority upgrading levers
BOF / EAF steel slag	$FeO–Fe_2O_3$ balance; basicity; free CaO/MgO; P-bearing phases; cooling history	Metallic/oxide Fe recovery; SCM potential; expansion; variable leaching	Hot-stage chemistry adjustment; controlled cooling; magnetic separation; carbonation
AOD / stainless / ladle slag	Cr oxidation state; spinel formation; C_2S polymorphism; MgO; sulfur	Cr immobilization/recovery; self-disintegration; binder potential	Cooling control; phase modification; carbonation; electric-field or sulfur-removal routes
Copper / fayalitic slag	Fe/Si ratio; matte/metal droplets; magnetite; viscosity; cooling rate	Cu recovery; Fe recovery; heat; glass/fiber products	CaO modification; controlled cooling; flotation; reduction; chlorination; leaching
Nickel / ferronickel slag	Pyroxene/olivine assemblage; Fe/Ni hosts; Ca/Mg availability	Fe/Ni recovery; mineral carbonation; glass-ceramics	Reduction; phase engineering; carbonation; glass-ceramic processing
FeMn / SiMn / ferrochrome slag	MnO/Cr-bearing phases; spinels; viscosity; basicity	Mn/Cr recovery; cast stone; detoxification	Reductive treatment; modifier addition; controlled crystallization; stabilization
Ti-bearing slag	Ti-bearing phases; impurity chemistry; reducible oxides; phase separability	Ti feedstock upgrading; Fe removal; high-value Ti route	UGS-type beneficiation; selective phase transformation; separation and impurity removal

Note. Author-developed synthesis based on Andersson et al. (2024, 2026), Ashrit et al. (2020), Baras et al. (2023), Goso et al. (2022), Guéguin and Cardarelli (2007), Jacob (2024), Kero Andertun et al. (2021), Kuanyshev et al. (2026), Li et al. (2025), Menad et al. (2021), Pistorius and Coetzee (2003), Vollbrecht et al. (2024), Xu et al. (2023), and Zietsman and Pistorius (2004).

Table 1 shows why one universal slag-treatment recipe is unrealistic. Steel slags are commonly constrained by basicity, free lime, iron, phosphorus, and chromium behavior; copper slags by iron-silicate structure, viscosity, droplets, and magnetite; and ferroalloy or Ti-bearing slags by the stability of specific oxide phases. Upgrading must therefore begin with the mineralogical state rather than with a generic material label.

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Figure 2 translates this mineralogical perspective into a state-transition model. It provides the conceptual bridge between characterization and the intervention classes compared in Section 4.

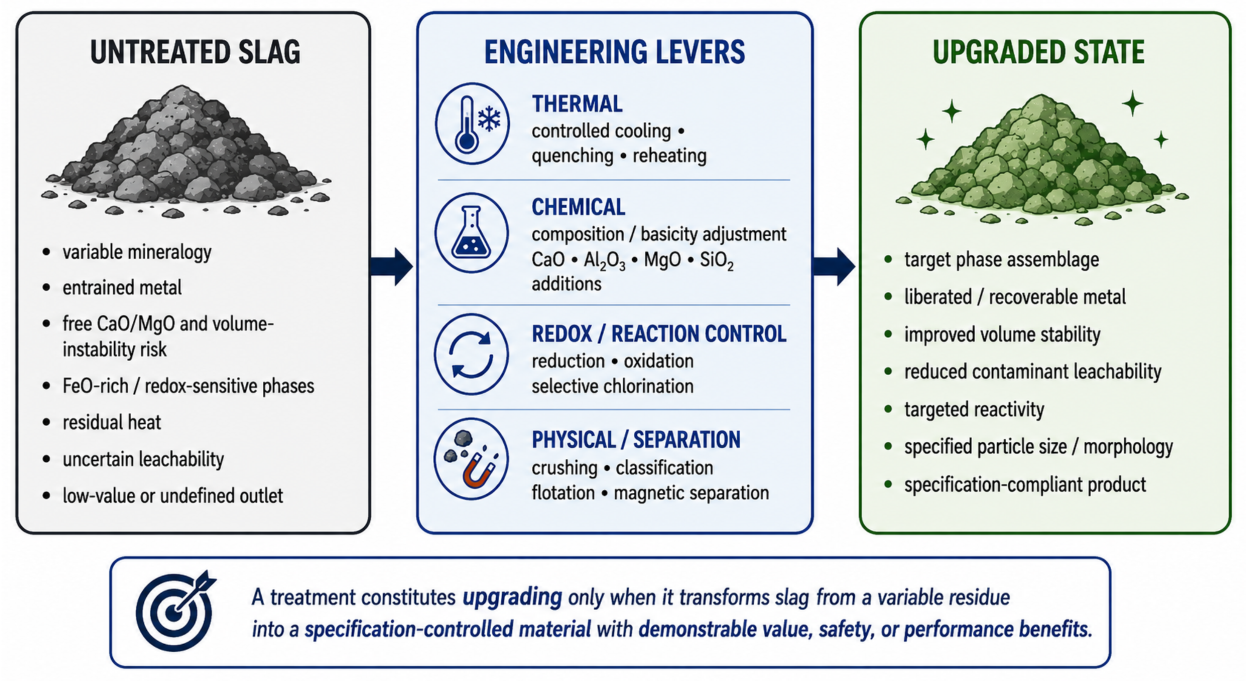

Figure 2. State-transition view of metallurgical slag upgrading.

Note. Author-developed synthesis based on Doschek-Held et al. (2025), Fan et al. (2026), Goso et al. (2022), Isaksson et al. (2023), and Liu et al. (2026).

The key implication of Figure 2 is that intervention is not the endpoint. The upgraded state must be defined by measurable specifications—metal liberation, dimensional stability, leaching control, reactivity, particle form, or another product attribute—otherwise the process remains treatment without demonstrated upgrading.

4. THERMAL, CHEMICAL, REDOX, AND HYBRID UPGRADING STRATEGIES

4.1 Thermal engineering

Thermal engineering is the most direct way to exploit the fact that slag leaves a furnace at high temperature and in a liquid state that can still be modified. Controlled cooling can promote or suppress crystallization, enlarge recoverable phases, preserve glassy reactivity, or direct valuable elements into separable hosts. Granulation can simultaneously address solidification and heat recovery, while slower or staged cooling can be advantageous when the goal is metal droplet settling, magnetite crystallization, or phase segregation (Barati & Jahanshahi, 2020; Gao et al., 2020; Sukurov et al., 2024; Wu et al., 2022; Wu et al., 2023; Zhang et al., 2023). The critical point is that the "best" cooling rate is product-specific: rapid quenching may benefit amorphous SCM production, whereas controlled crystallization may be necessary for metal liberation or glass-ceramic manufacture..

4.2 Chemical and additive-based modification

Chemical modification operates on the same principle by shifting the liquid composition before solidification. Adding CaO to iron-silicate copper slag has been shown to alter settling behavior and downstream leaching characteristics, demonstrating how a modifier can simultaneously affect viscosity, phase formation, and metal separation (Isaksson et al., 2023; Kero Andertun et al., 2021). In steel slags, hot-stage additions and slag-to-slag blending can alter basicity, promote desired mineral phases, and improve cementitious or separation behavior (Chandel et al., 2025; S. Hao et al., 2024). However, the dissolution behavior of additives is itself a kinetic limitation, so successful modification requires attention to particle size, mixing, residence time, and the liquid fraction available for reaction (Halwax et al., 2025; C. Zhang et al., 2021; Zhang et al., 2022). BOF modification also alters the dissolution of phosphorus-bearing phases, underscoring why modifier selection must consider both product formation and impurity deportment (Yu et al., 2022).

4.3 Reductive and oxidative treatments

Reductive treatment is used when valuable metals are predominantly present as oxides or when iron recovery can yield a cleaner residual silicate matrix. Carbothermal and aluminothermic reduction, along with online smelting-reduction approaches, have been investigated for steel, copper, manganese, and mixed metallurgical residues. These routes can achieve high transformation intensity by fundamentally re-partitioning oxygen between metal and slag, but they also pose new challenges: carbon or reductant consumption, furnace energy demand, alloy quality control, phosphorus transfer, and the need to valorize the post-reduction slag (Krammer et al., 2026; Kuang et al., 2026; Kudyba et al., 2021; Kudyba & Safarian, 2022; Liu et al., 2026).

Oxidative treatment can be equally strategic. Oxidation may promote magnetite or spinel formation, change the distribution of chromium, or create reactive iron-oxide-rich structures for catalytic or separation applications. Cooling control and self-wrapped spinel precipitation provide an example of using oxidation state and crystallization together to reduce chromium hazard (Cao et al., 2025). Oxidative modification followed by molten chlorination is a more intensive example in copper slag, where the objective is to alter phase chemistry prior to selective volatilization or separation (G. Wang et al., 2026).

4.4 Hybrid routes and intervention hierarchy

Electrochemical and other hybrid routes further broaden the toolbox for upgrading. Electrochemical reduction of complex oxide slags, electric-field-assisted sulfur migration, selective leaching, alkali activation, carbonation, and combined physical–chemical separation all demonstrate that upgrading need not be a single-furnace step (Martin-Treceno et al., 2021; Zhou et al., 2026). However, the more integrated the route becomes, the more important it is to evaluate system-level effects. A treatment that improves one recovery metric but produces a difficult liquid effluent, an unstable residue, or a high-energy separation step may shift rather than solve the original problem.

The evidence therefore supports a hierarchy of intervention. Low-intensity routes—controlled cooling, crushing, magnetic separation, flotation, or modest chemical adjustments—should be preferred when they meet the product target. High-intensity smelting, chlorination, or electrochemical treatment is justified when the inventory value is correspondingly high or when the route simultaneously addresses multiple constraints. This hierarchy is important because "more processing" is not synonymous with "more upgrading"; the correct benchmark is net value creation after accounting for material, energy, environmental, and integration penalties (Sui et al., 2026).

Table 2 compares the principal upgrading strategies by the transformation they impose, their strongest advantage, the main scale-up constraint, and the maturity of the available evidence.

Table 2. Critical comparison of major scale-up strategies

Strategy	Primary transformation	Main advantage	Critical constraint	Indicative maturity
Controlled cooling/granulation	Phase size, glass fraction, solidification path, recoverable heat	Can exploit hot slag without major chemistry change	Product-specific cooling window; heat-transfer and fouling constraints	Pilot to industrial for selected systems
Chemical modification	Basicity, network structure, viscosity, crystallization sequence	Can improve settling, stability, reactivity, or separation before solidification	Modifier dissolution, mixing, refractory compatibility, added mass	Laboratory to industrial case evidence
Reductive / smelting treatment	Oxides → metal/alloy; residual silicate composition	High metal-recovery potential; strong phase separation	Energy/reductant use; alloy impurities; post-reduction slag quality	Laboratory to demonstration / online concepts

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Strategy	Primary transformation	Main advantage	Critical constraint	Indicative maturity
Oxidative / chlorination treatment	Valence state, spinel/magnetite formation, volatile chlorides	Can selectively immobilize or separate targeted species	Gas handling, reagent control, corrosion, emissions	Mostly laboratory / emerging
Physical beneficiation	Liberation, magnetic response, density, flotation response	Low complexity when valuable phases are already separable	Requires adequate phase size and liberation	Industrial for selected copper/steel slags
Reactive conversion / electrochemical	Carbonation, dissolution, ion migration, electroreduction	Can couple hazard control with material or metal value	Mass transfer, reagent/energy demand, scale-up complexity	Laboratory to pilot; selected industrial carbonation

Note. Author-developed synthesis based on Barati and Jahanshahi (2020), Cao et al. (2025), Chandel et al. (2025), Doschek-Held et al. (2025), Gao et al. (2020), Halwax et al. (2025), Isaksson et al. (2023), Krammer et al. (2026), Liu et al. (2026), Martin-Treceno et al. (2021), G. Wang et al. (2026), Wu et al. (2022), C. Zhang et al. (2021), Zhang et al. (2022), and Zhou et al. (2026).

The comparison highlights a practical asymmetry: low-intensity thermal and physical routes are easier to integrate but may be insufficient for chemically locked metals, whereas redox, chlorination, or electrochemical routes can create stronger selectivity at the cost of higher process complexity. Chemical modification occupies an intermediate position and is particularly powerful when applied to hot slag before solidification.

Figure 3 is inserted after this comparison to show that technology classes are not independent. Each route acts on a common set of control variables and may be combined when one intervention cannot satisfy the full product specification.

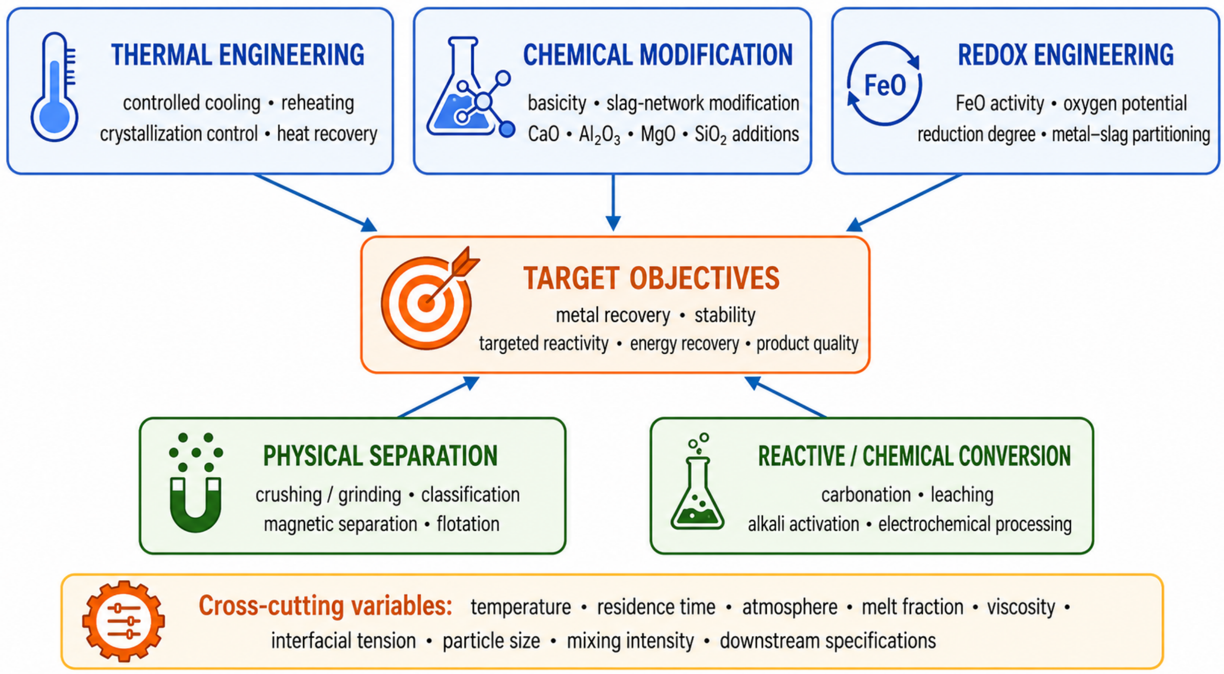

Figure 3. Classification of upgrading strategies and dominant control variables.

Note. Author-developed synthesis based on Barati and Jahanshahi (2020), Chandel et al. (2025), Halwax et al. (2025), Krammer et al. (2026), Martin-Treceno et al. (2021), G. Wang et al. (2026), Wu et al. (2022), and Zhou et al. (2026).

The figure also reinforces the need to define a target function before selecting a treatment. Cooling rate, basicity, oxygen potential, liberation, and carbonation conditions are design variables, not objectives; they are valuable only insofar as they deliver a qualified metal, material, energy, or environmental outcome.

5. METAL RECOVERY AND RESOURCE EFFICIENCY

5.1 Phase occurrence and separability

Metal recovery is the most intuitive driver of slag upgrading, but the literature shows that recovery performance depends on how the metal occurs, not just on total grade. In steel slags, metallic iron and iron-rich phases can be recovered by crushing, magnetic separation, or reduction; in copper slags, recovery may involve settling, flotation, reduction, leaching, or combinations of these operations. Hydrometallurgical reviews and characterization studies reinforce the need to match the separation method to mineral hosts and liberation characteristics (Binnemans et al., 2020; Liu & Bao, 2024; Liu et al., 2023; Menad et al., 2021).

5.2 Copper slag as an industrially relevant model

Copper slag provides some of the strongest industrial and mechanistic evidence. Industrial flotation case studies show that slag can be treated as a secondary ore when valuable copper remains in recoverable phases, while mechanistic studies of nucleation, cooling, and reduction demonstrate how upstream phase engineering can make downstream separation more effective (Chen et al., 2025; Gao et al., 2020; Pavez et al., 2021; Valderrama et al., 2024). This is a central insight into upgrading: separation efficiency is often determined before the separator, during liquid-state reactions, cooling, and phase growth. The strength of this evidence cluster is reinforced by industrial-scale quantitative results: Valderrama et al. (2024) reported a 27.9% Cu concentrate at 87.5% Cu recovery while processing 1344 t/day, demonstrating that slag treatment can function as a genuine secondary-ore operation rather than merely a laboratory recovery concept.

5.3 Reductive, pyrometallurgical, and hydrometallurgical recovery

Reductive routes expand the recovery envelope to include chemically bound metals. Multi-source residue treatment, carbothermal reduction, online EAF slag reduction, and aluminothermic processing of MnO-bearing slags demonstrate that slag can be deliberately converted into an alloy or metallic phase plus a lower-metal residual matrix (Hanke et al., 2022; Krammer et al., 2026; Kudyba et al., 2021; Kudyba & Safarian, 2022; Liu et al., 2026). Co-treatment can also be used strategically: copper slag may supply iron, while battery or other residues contribute Ni and Co, or steelmaking and copper slags can be combined to redistribute phosphorus, silicon, and iron (Cheng et al., 2026; Z.-H. Yang et al., 2026).

Hydrometallurgy remains relevant for selective dissolution, enabling metal recovery without remelting the entire matrix. Copper-slag leaching studies show that chemical and biological routes can recover metals while producing a residue potentially suitable for cementitious use, provided residual contaminants and reactivity are controlled (Kinnunen et al., 2020). The most robust flowsheets are therefore not purely pyrometallurgical or hydrometallurgical; they use the process that best matches each element and phase.

Strategic and specialty metals increase the economic rationale for upgrading. Manganese, chromium, vanadium, cobalt, nickel, and precious metals may occur at lower concentrations than iron but can dominate the value if they are selectively recoverable. Work on manganese reduction, cobalt-bearing fayalitic model slags, chromium-containing metallurgical residues, and precious-metal recovery illustrates the range of opportunities and the importance of speciation control (Kudyba et al., 2021; Samanta et al., 2023; Vollbrecht et al., 2024; Xu et al., 2023).

5.4 Recovery–residue co-optimization

Resource efficiency must also account for post-recovery residue. A metal-recovery route is incomplete if it produces a silicate slag that still requires disposal. Conversely, processes that couple metal recovery with a cementitious, glassy, carbonatable, or otherwise useful residual matrix can generate two revenue or avoidance streams. Examples of this broader resource-integration logic include converting fayalitic slag into pig iron and glass fibers, and using the heat from copper slag to produce copper-containing weathering steel (Blenau et al., 2023; J. Hao et al., 2024).

For industrial decision-making, metal recovery should therefore be evaluated using at least four metrics: recoverable metal mass, product grade and penalty elements, energy/reductant requirement, and value or disposal burden of the residual slag. The first metric alone is insufficient and can favor technically impressive but economically weak flowsheets (Lin et al., 2021).

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To make the link between phase engineering and separation explicit, Table 3 summarizes the recovery logic for major target metals and identifies the primary trade-off to be controlled in each case.

Table 3. Metal-recovery logic for upgraded metallurgical slags

Target	Typical occurrence in slag	Useful upstream conditioning	Separation route	Critical trade-off
Fe	Metallic Fe, FeO-bearing silicates, ferrites, magnetite	Reduction, crystallization, phase aggregation, cooling control	Magnetic separation, settling, smelting separation	P/Si transfer; energy use; value of residual silicate
Cu	Matte/metal droplets, sulfides, oxide/silicate-associated Cu	CaO modification, slow/controlled cooling, reduction	Settling, flotation, smelting, leaching	Viscosity and magnetite control; residue quality
Ni/Co	Metal/alloy droplets or oxide/silicate hosts	Co-smelting, reduction, selective phase engineering	Alloy separation, leaching, downstream refining	Selectivity vs Fe; alloy penalty elements
Mn / Cr	Oxides, spinels, complex silicates	Alumino-/carbothermal reduction; valence/phase control	Metal/alloy recovery; magnetic or chemical separation	High stability of spinels; environmental control
V / Ti	Complex titanate/vanadate phases	Selective reduction/oxidation and phase transformation	Beneficiation, electrochemical or chemical separation	Need high selectivity; downstream feedstock specifications
Precious /strategic metals	Minor phases, inclusions, entrained droplets	Concentration, liberation, phase-selective treatment	Flotation, leaching, smelting/refining	Small mass but high value; analytical and recovery complexity

Note. Author-developed synthesis based on Binnemans et al. (2020), Chen et al. (2025), Cheng et al. (2026), Hanke et al. (2022), Kinnunen et al. (2020), Kudyba et al. (2021), Kudyba and Safarian (2022), Liu et al. (2026), Liu and Bao (2024), Liu et al. (2023), Pavez et al. (2021), Samanta et al. (2023), Valderrama et al. (2024), Vollbrecht et al. (2024), and Z.-H. Yang et al. (2026).

A recurring pattern is evident: the most difficult recovery problems are those in which the target element is dispersed in stable oxides or spinels rather than concentrated in discrete metallic or sulfide phases. In such cases, upgrading must first create a separable phase before conventional mineral processing can be effective.

Figure 4 therefore presents metal recovery as a cascade rather than a single unit operation, connecting phase engineering to separation, recycle, and post-recovery residue valorization.

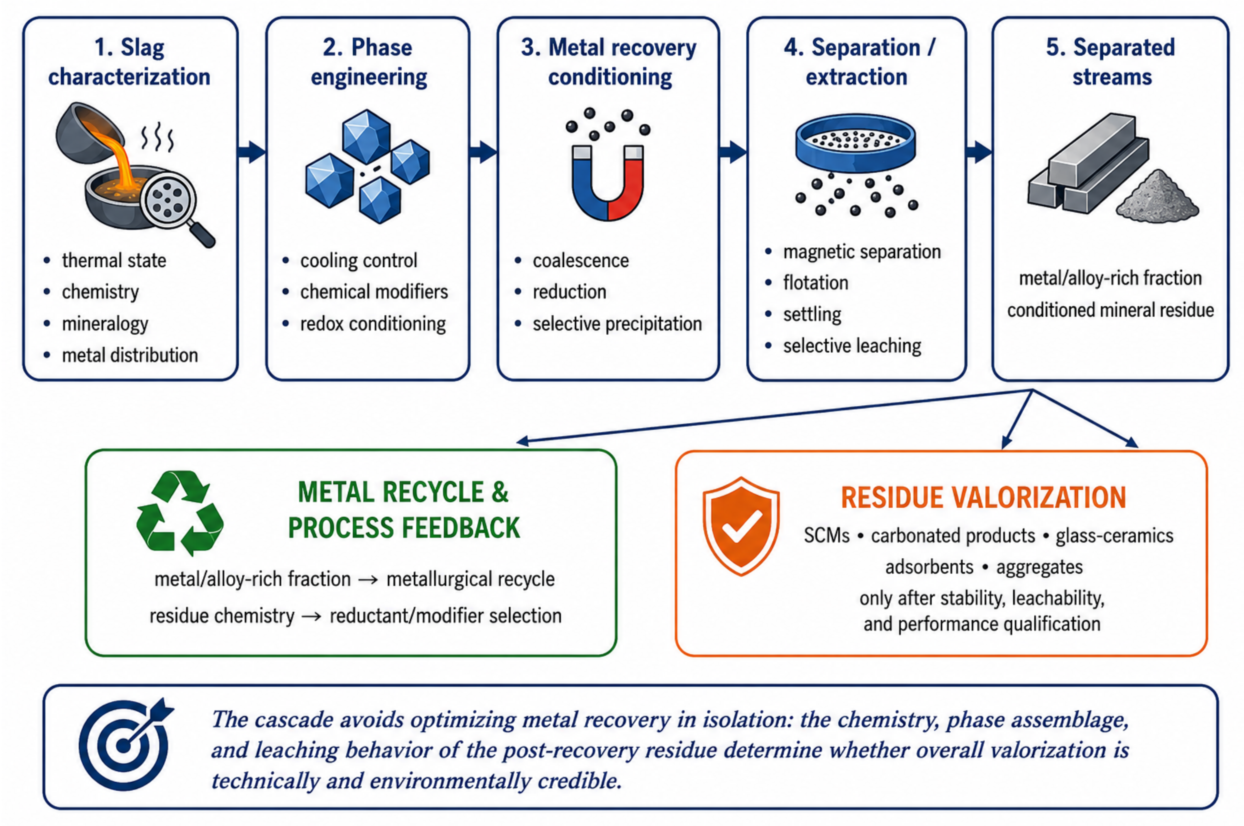

Figure 4. Integrated metal-recovery cascade for upgraded slags.

Note. Author-developed synthesis based on Binnemans et al. (2020), Chen et al. (2025), Hanke et al. (2022), Kinnunen et al. (2020), Liu et al. (2026), Pavez et al. (2021), Samanta et al. (2023), Valderrama et al. (2024), and Z.-H. Yang et al. (2026).

The cascade concept is especially important for critical reviews of slag treatment because it prevents recovery percentage from becoming the sole performance indicator. The residual slag enters a second value pathway, and its chemistry can determine whether the overall process is circular or merely redistributive.

6. CONSTRUCTION MATERIALS AND HIGH-VALUE FUNCTIONAL PRODUCTS

6.1 Cementitious and construction products

The construction sector remains the largest potential sink for metallurgical slags, but modern upgrading changes the question from "Can slag be used in concrete?" to "What conditioning makes a specific slag a reliable cementitious or aggregate product?" EAF, BOF, AOD, ladle, and engineered slags differ substantially in glass content, hydraulic reactivity, free lime, iron-rich phases, and setting behavior. Studies on EAF slag, low-energy steel slag powders, engineered slags, BOF slag activation, and next-generation EAF slag demonstrate that chemical and thermal conditioning can move materials into more useful reactivity windows (Andersson et al., 2024; Bullerjahn & Bolte, 2022; Carvalho et al., 2023; Liu et al., 2024; Schneider et al., 2026; Stefanini et al., 2024). Comparative evaluation of alternative EAF-slag binder pathways further shows that pretreatment intensity must be matched to the intended binder function rather than assumed beneficial by default (Machini et al., 2026).

Hot-stage modification is particularly attractive because it can create cementitious value before the slag has fully solidified. This avoids some of the energy penalty associated with remelting or intensive post-treatment and can exploit existing furnace heat. However, the route is sensitive to composition, mixing, cooling, and the resulting mineral assemblage. The evidence on EAF and BOF modification suggests that product-oriented slag design is more promising than assuming that all steel slags can be activated after the fact (Chandel et al., 2025; S. Hao et al., 2024; Isaksson et al., 2026).

6.2 Glass-ceramics, cast stone, and fibers

Glass-ceramics, cast stone, and fibers represent higher-value but more composition-sensitive pathways. These products exploit the silicate nature of many slags but require deliberate control of glass formation, nucleation, crystallization, shrinkage, and contaminant immobilization. Stainless-steel slag glass-ceramics illustrate how the SiO_2/Al_2O_3 ratio can affect crystallization and heavy-metal immobilization; ferronickel and silicomanganese slags can be directed toward glass-ceramic or cast-stone products when their phase evolution is controlled (Deng et al., 2022; Huang, Li, Cheng, et al., 2025; Huang, Li, Zhou, et al., 2025; Huang et al., 2026; Shang et al., 2021; Stabile et al., 2025). The holistic conversion of fayalitic slag to iron and glass fibers demonstrates the additional benefit of combining metal and material recovery (Blenau et al., 2023).

6.3 Reactive conversion and functional products

Reactive conversion enables the production of a range of products. Carbonated slags can become SCMs, carbonate-bonded blocks, or mineralized products; steel slag can be processed to produce nano-$CaCO_3$; blast-furnace slag can be converted into zeolite and $CaCO_3$; and alkali activation can transform metallurgical slags into binders or composite matrices (Grengg et al., 2024; Lancellotti et al., 2021; Lee et al., 2020; Shin & Kim, 2026; Srivastava et al., 2022). These routes are appealing because they can couple waste utilization with CO_2 uptake or reduce clinker demand, but they require careful accounting of pretreatment, grinding, reagent use, curing, and long-term durability.

Functional-material applications are smaller in volume but potentially higher in value. Structure-modified steel slags have been investigated as catalysts, nanosorbents, and catalytic or adsorptive materials for pollution control. Microwave-driven phase reconstruction can create active iron-bearing structures for simultaneous SO_2/NOx adsorption. Broader reviews document the catalytic, photocatalytic, electrocatalytic, and carbon-capture functions of modified slag (Kholkina et al., 2020; Kim et al., 2026; F.-P. Wang et al., 2021; Wang et al., 2025). These applications should be judged against commercial functional materials rather than against landfill cost alone; otherwise, high apparent "value" can mask poor performance or small addressable markets.

The reviewed literature also includes slags produced during the smelting of metallurgical dusts and lateritic fines, in which the resulting Ca-rich matrices can be used for cementitious applications (Tzevelekou et al., 2020). Such examples reinforce a broader principle: the final slag should be designed together with the primary metal-recovery process whenever possible. If product requirements are considered only after smelting, the composition window may already be too constrained for high-value valorization.

6.4 Market fit and product strategy

Product diversification is therefore not inherently desirable. A high-volume, lower-margin SCM route may outperform a high-value specialty material if it is robust, local, and compatible with continuous slag generation. Conversely, an advanced product can be attractive when the slag supply is smaller, compositionally controlled, and located near a suitable market. The correct metric is not unit price alone, but value multiplied by realistic market volume and adjusted for quality-control costs.

Table 4 organizes material applications by the transformation needed to make the slag fit for purpose, rather than by listing end uses alone.

Table 4. Product-oriented valorization routes for upgraded slags

Product route	Required transformation	Primary quality gate	Key limitation	Best-fit context
SCM / blended binder	Increase reactive glass or suitable hydraulic phases; control free lime	Strength contribution, setting, soundness, leaching	High Fe/crystalline content; composition variability	Large local cement market; consistent slag stream
Aggregate / carbonate-bonded block	Stabilize free CaO/MgO and contaminants	Volume stability, abrasion, leaching	Low unit value; transport sensitivity	High-volume regional construction
Glass-ceramic / cast stone/fiber	Control glass-forming composition and crystallization	Mechanical properties, shrinkage, phase uniformity	Energy and composition window	Silicate-rich slag with controlled supply

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Product route	Required transformation	Primary quality gate	Key limitation	Best-fit context
Carbonated mineral product	Expose reactive Ca/Mg and control carbonation	CO_2 uptake plus durability/stability	Grinding, gas conditioning, curing time	Co-located CO_2 and slag sources
Catalyst/adsorbent / sorbent	Create active Fe-bearing phases, porosity, surface functionality	Activity, selectivity, regeneration, contaminant safety	Small market; product consistency	Low-volume, composition-controlled slag
Zeolite / $CaCO_3$ / specialty chemicals	Selective dissolution/precipitation / hydrothermal conversion	Purity and yield	Reagent demand and liquid-effluent management	High-value chemistry with integrated reagent recycle

Note. Author-developed synthesis based on Blenau et al. (2023), Bullerjahn and Bolte (2022), Carvalho et al. (2023), Deng et al. (2022), Grengg et al. (2024), Huang, Li, Cheng, et al. (2025), Huang, Li, Zhou, et al. (2025), Huang et al. (2026), Kholkina et al. (2020), Kim et al. (2026), Lancellotti et al. (2021), Lee et al. (2020), Machini et al. (2026), Schneider et al. (2026), Shang et al. (2021), Shin and Kim (2026), Srivastava et al. (2022), Stabile et al. (2025), Stefanini et al. (2024), F.-P. Wang et al. (2021), and Wang et al. (2025).

The table indicates that construction and functional applications occupy very different market spaces. SCMs and aggregates can absorb large tonnages but tolerate only limited variability in soundness and environmental performance. Functional products can justify more intensive processing, but they demand tighter quality control and face smaller markets.
Figure 5 converts these product routes into a quality-gate model. A technically interesting material should not advance unless it passes chemistry, dimensional-stability, environmental, performance, and market checks.

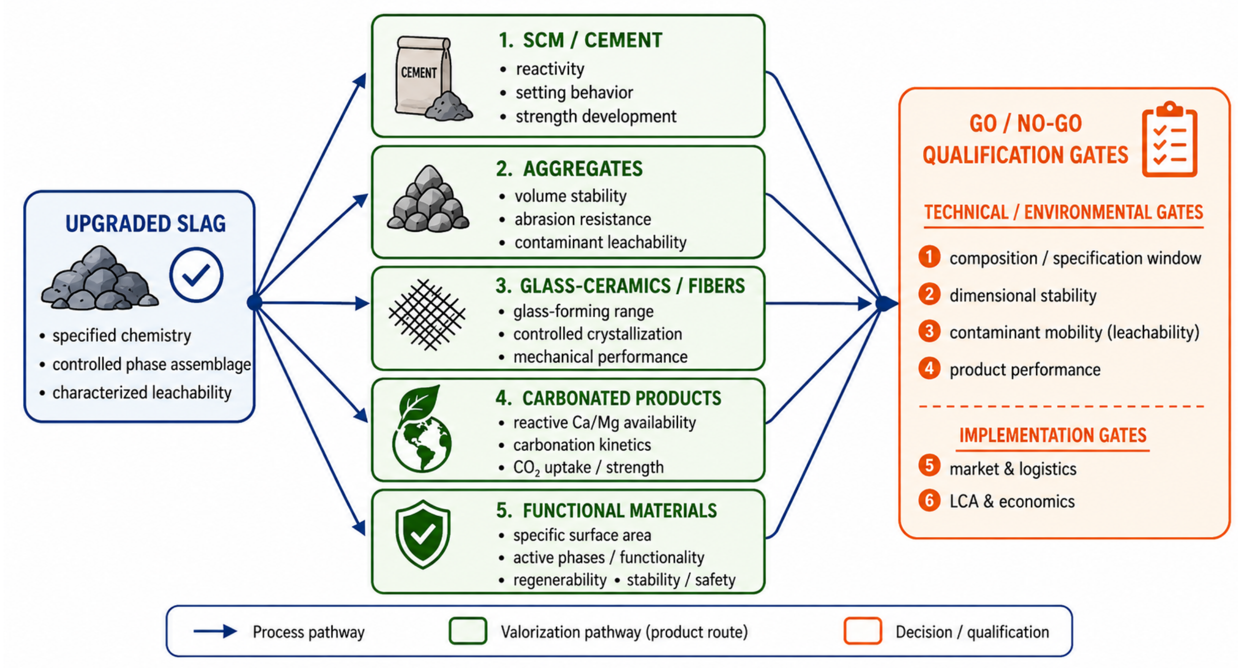

Figure 5. Product pathways and quality gates for upgraded slags.

Note. Author-developed synthesis based on Bullerjahn and Bolte (2022), Carvalho et al. (2023), Deng et al. (2022), Kholkina et al. (2020), Kim et al. (2026), Lee et al. (2020), Schneider et al. (2026), Shin and Kim (2026), Srivastava et al. (2022), and F.-P. Wang et al. (2021).

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This gate-based view is a useful safeguard against overclaiming high-value valorization. A slag-derived catalyst or glass-ceramic may demonstrate excellent laboratory performance, but the industrial proposition remains incomplete until reproducibility, contaminant control, market volume, logistics, and end-of-life behavior are addressed.

7. ENVIRONMENTAL STABILITY, CARBONATION, AND ENERGY INTEGRATION

7.1 Environmental stability and leaching

Environmental performance is inextricably linked to upgrading because many treatments intentionally alter the phases that govern element mobility. Chromium is a prominent example. Carbonation, cooling control, spinel formation, and cementitious immobilization can reduce leaching, but the effect depends on oxidation state, phase stability, and exposure conditions rather than on total chromium concentration alone (Cao et al., 2025; Gu et al., 2026; Kuanyshev et al., 2026; Wang, Tao, et al., 2021; Wang, Zeng, et al., 2021; Wang et al., 2020). Therefore, environmental qualification must be performed on the final upgraded product, not inferred from the untreated slag.

7.2 Carbonation and carbon accounting

Carbonation is among the most widely studied reactive conversion routes because steel and some ferroalloy slags contain Ca- and Mg-bearing phases that can bind CO_2. Direct aqueous carbonation, phase-specific reactivity studies, ferronickel-slag engineering, stainless-steel slag phase modification, and dedicated carbonation equipment demonstrate that carbon uptake can be deliberately increased by altering mineralogy, particle size, and transport conditions (Bonfante et al., 2025; Peys et al., 2025; Ragipani et al., 2021; Yang et al., 2024; Zhao et al., 2020; Zhou et al., 2025). Carbonation can also improve volume stability or reduce leaching, making it a multifunctional treatment rather than a carbon storage step in isolation.

The carbon benefit is nevertheless process-dependent. Grinding, heating, pressurization, chemical additives, transport, and curing may offset some of the captured CO_2, while the avoided impact depends on what product the carbonated slag displaces. LCA studies of steel slag treatment and nickel-slag valorization show why system boundaries and counterfactual products are decisive (Li et al., 2024; Quéheille et al., 2021; J. Yang et al., 2026). A kilogram of CO_2 mineralized is therefore not equivalent to a kilogram of net climate benefit.

7.3 Thermal-energy integration

Thermal energy is another often underused value stream. Molten slag contains recoverable sensible heat, but recovery is challenging because it solidifies, fouls surfaces, and often has low thermal conductivity. Centrifugal granulation has been proposed and analyzed as a means to combine particle formation with heat recovery. Industrial hot-slag tests and broader decarbonization studies demonstrate the potential value of integrating material and energy recovery (Fernández-González et al., 2024; Lv et al., 2026; Wu et al., 2022; Wu et al., 2023; T. Zhang et al., 2021). The strongest opportunity is typically at the hot stage, before the slag cools and exergy is irreversibly lost.

Recent work on carbon-negative steel-slag mineralization using industrial flue gas further illustrates the convergence of carbon management and slag processing (X. Wang et al., 2026). Such routes are especially interesting when the gas source, slag source, and product market are co-located, because transport and gas-conditioning burdens can otherwise dominate the system.

A credible environmental assessment of an upgrading route should therefore address at least five endpoints: net greenhouse-gas effect, contaminant leaching, volume stability and weathering, water and reagent demand, and the fate of secondary emissions or effluents. The literature increasingly recognizes these interactions, but long-term field durability and harmonized leaching protocols remain less mature than short-term laboratory performance.

8. PROCESS INTEGRATION AND INDUSTRIAL READINESS

8.1 The laboratory-to-industry integration gap

The gap between laboratory feasibility and industrial deployment is often determined by integration rather than chemistry. A laboratory process may involve finely ground slag, a long residence time, pure reagents, a controlled atmosphere, and batch operation. A steel or copper plant must handle variable hot feed, refractory constraints, dust and gas systems, maintenance access, throughput, product logistics, and the economic value of furnace time. Industrially relevant studies therefore carry disproportionate weight when assessing readiness (Buyle et al., 2021; Falsafi et al., 2023; Fan et al., 2025; Kek et al., 2026; Rieger et al., 2021).

Several evidence clusters are comparatively mature. Industrial copper-slag flotation has been demonstrated in plant case studies (Pavez et al., 2021; Valderrama et al., 2024); CaO modification of iron-silicate slags has been investigated from laboratory to industrial scale and linked to both metal settling and downstream material use (Isaksson et al., 2026; Isaksson et al., 2023; Kero Andertun et al., 2021); and centrifugal granulation or hot-slag energy-recovery concepts have progressed beyond purely conceptual assessment (Wu et al., 2023; T. Zhang et al., 2021). These examples show that successful implementation usually couples a simple transformation objective with existing handling infrastructure.

8.2 Hot-stage processing, monitoring, and control

Online or hot-stage smelting reduction is more intensive but potentially transformative. EAF slag reduction via Al_2O_3 modification, integrated multi-metal recovery, and new smelter concepts for green-steel raw-material loops aim to treat the slag before it becomes a cold waste stream (Hanke et al., 2022; Liu et al., 2026; Voraberger et al., 2026). The advantage is process intensification; the risk is that slag treatment competes with primary metallurgy for furnace capacity, energy, refractory life, or process control.

Digital and process-control requirements also increase with the intensity of transformation. Hot modification requires reliable dosing and mixing; controlled cooling requires temperature and solidification control; redox processes require oxygen potential and endpoint management; and multi-stage routes require compositional feedback between metal and residual slag. Experimental work on additive dissolution and in situ conductivity monitoring demonstrates how sensing and kinetics can be incorporated into such control strategies (Halwax et al., 2025; Zhang et al., 2023). Electric-field-assisted slag treatment adds another layer of controllability but also additional equipment complexity (Zhou et al., 2026).

8.3 Operational readiness rubric and system assessment

Readiness is assessed using the operational definitions established in Section 2.3 rather than by assigning an unsupported numeric TRL. The key question is not whether an individual unit operation is mature, but whether representative feed, phase transformation, separation, product specification, environmental control, and continuous integration have been demonstrated together. This distinction is especially important for flowsheets that combine mature crushing, flotation, leaching, or smelting operations with a novel hot-stage or phase-engineering step.

Techno-economic and multi-criteria studies provide a bridge between laboratory and deployment. Full-chain blast-furnace slag utilization, multi-criteria assessment of secondary-metallurgy slag, ex-ante LCA, and life-cycle trade-off analyses show that the preferred route can change once capital intensity, energy, avoided disposal, product substitution, and plant constraints are included (Duan et al., 2022; Falsafi et al., 2023; J. Yang et al., 2026). This is also why patent activity and industrial roadmaps are useful complementary evidence of where the sector is investing, even when academic performance data remain incomplete (Fan et al., 2025).

Within the 111-study recent corpus, explicit plant-scale or industrial-scale evidence is concentrated in a relatively small set of pathways, including industrial copper-slag flotation, laboratory-to-industrial CaO modification of iron-silicate slags, selected hot-slag heat-recovery tests, and recent industrial mineralization trials. The resulting evidence landscape therefore supports a conservative interpretation of readiness rather than broad claims based solely on the volume of laboratory publications.

Table 5 screens representative pathways from an industrial-readiness perspective and deliberately separates unit-operation maturity from flowsheet maturity.

Table 5. Industrial-readiness screen for representative slag-upgrading pathways

Pathway	Integration opportunity	Evidence maturity	Dominant implementation risk	Industrial decision criterion
Copper slag flotation	Uses conventional mineral-processing equipment after controlled cooling	Industrial case studies	Feed variability and liberation	Recoverable Cu value vs grinding/flotation cost
CaO-modified copper slag	Modifier added while slag is hot; settling before solidification	Laboratory to industrial-scale evidence	Mixing, viscosity window, refractory and dosing control	Incremental Cu recovery plus downstream residue value

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Pathway	Integration opportunity	Evidence maturity	Dominant implementation risk	Industrial decision criterion
Steel slag magnetic/physical recovery	Can fit existing crushing and metal-recovery circuits	Industrially mature unit operations	Fine locked Fe and variable slag mineralogy	Recovered Fe value and residual product specification
Hot-stage EAF / BOF modification	Uses sensible heat and can tailor phases before cooling	Pilot/emerging industrial evidence	Furnace/ladle capacity, control, product consistency	Avoided remelting + qualified SCM or recovered metal
Centrifugal granulation + heat recovery	Combines solidification and thermal-energy recovery	Beyond concept; pilot/scale analyses	Heat-transfer efficiency, fouling, continuous reliability	Recoverable heat plus usable granulated product
Carbonation/mineralization	Can use local flue gas and stabilize reactive phases	Laboratory to industrial trial evidence	Gas/solid mass transfer and net carbon balance	Net CO_2 benefit + qualified product + low reagent burden

Note. Author-developed synthesis based on Buyle et al. (2021), Duan et al. (2022), Falsafi et al. (2023), Isaksson et al. (2023, 2026), Liu et al. (2026), Pavez et al. (2021), Rieger et al. (2021), Valderrama et al. (2024), X. Wang et al. (2026), Wu et al. (2023), J. Yang et al. (2026), and T. Zhang et al. (2021). Maturity refers to the integrated pathway, not merely to the maturity of individual unit operations.

The strongest near-term cases are those that can be inserted into established slag-handling, mineral-processing, or gas-management infrastructure. The weakest are not necessarily the most novel chemistries, but those that require many new interfaces between hot material handling, reagents, energy, effluent treatment, and product qualification.

9. COMPARATIVE PERFORMANCE, TEA/LCA, AND ALTERNATIVE ROUTES

9.1 Choosing the correct baseline

Slag upgrading should be compared against the best available alternative, not against an unrealistic “do nothing” baseline. In many locations, conventional aggregate use, direct cementitious use, or established metal recovery already has low marginal cost. An upgrading process must therefore generate sufficient additional value or risk reduction to justify the investment in new capital, energy, reagents, quality control, and logistics. Consequential and prospective LCA studies emphasize that substitution credits and regional markets can strongly affect the ranking of alternatives (Di Maria & Van Acker, 2021; Li et al., 2024; Quéheille et al., 2021). Granulation and direct use are attractive when the slag composition is already compatible with a large market and when residual metals are too dilute to justify recovery. Carbonation becomes more attractive when reactive Ca/Mg phases are abundant, local CO_2 is available, and the carbonated product has a real outlet. Smelting reduction is favored when reducible metal value is high enough, and the residual slag can be converted into a useful material. High-value functional products are credible when the market is sufficiently large, and the quality specification can be consistently met.

9.2 Quantitative benchmarking without false equivalence

Quantitative comparisons are useful only when the underlying feed, operating conditions, and product definition remain visible. Table 6 therefore reports representative performance indicators rather than pooled averages. The cases span a titanium feedstock route, industrial copper slag phase modification, industrial flotation, and hot slag heat recovery. They are intentionally heterogeneous: the purpose is to show which metric defines success for each pathway and why a single recovery percentage cannot rank all technologies.

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Table 6. Representative quantitative benchmarks for different slag-upgrading functions

Route/system	Representative condition	Quantitative result	Product/residue implication	Evidence scale
Modified UGS, Ti-bearing slag	Roast–leach beneficiation of fluxed titaniferous slag	90.5 mass% TiO_2 product; 83% TiO_2 recovery	Target Ti grade achieved, but impurity and particle-size constraints remained	Experimental process study
CaO-modified copper slag settling	Industrial CaO modification; settling-furnace conditions	Overall Cu recovery increased 63→88% as viscosity decreased 0.51→0.25 Pa·s	Lower viscosity and Cu solubility improve settling; operating temperature remains critical	Industrial trial + laboratory characterization
Copper-slag flotation, HVL smelter	Industrial rougher/cleaner circuit; 1344 t/day	27.9% Cu concentrate; 87.5% Cu recovery	Commercially relevant concentrate from slag treated as secondary ore	Industrial operation
Hot steel-slag heat recovery	In-situ industrial heat-recovery tests	Heat-recovery efficiency reported at approximately 74% in the cited industrial test	Demonstrates thermal value recovery before exergy is lost during cooling	Industrial test

Note. Values are representative study-specific results and are not pooled or directly rankable because feed compositions, system boundaries, and product specifications differ. Sources: Goso et al. (2022); Isaksson et al. (2023); Valderrama et al. (2024); T. Zhang et al. (2021).

Table 6 shows the asymmetry of technology assessment. UGS-type beneficiation is judged against Ti-feedstock chemistry and recovery; copper-slag settling is controlled by viscosity, dissolved versus entrained copper, and droplet behavior; flotation is judged against recovery, concentrate grade, throughput, and tailing quality; and heat-recovery systems must be assessed by recovered energy together with the usability of the cooled product. Quantitative evidence therefore strengthens the review only when each metric remains tied to its process function.

9.3 TEA/LCA and system-level decision variables

System assessment frequently changes the apparent ranking obtained from laboratory recovery data. Ex-ante LCA, prospective LCA, techno-economic analysis, consequential assessment, and multi-criteria decision studies repeatedly identify electricity mix, thermal integration, transport, avoided disposal, product displacement, reagent demand, plant utilization, and coproduct credit as ranking variables (Buyle et al., 2021; Di Maria & Van Acker, 2021; Duan et al., 2022; Falsafi et al., 2023; Li et al., 2024; Quéheille et al., 2021; J. Yang et al., 2026). Table 7 makes these boundary conditions explicit.

Table 7. System-assessment evidence and decision variables relevant to slag-upgrading selection

Study / route	Assessment type	Reference alternative / boundary	Dominant decision variables	Critical use in this review
Buyle et al. (2021), emerging carbon-steel slag treatments	Ex-ante LCA	Lab observation scaled toward industrial production	Scale-up assumptions, electricity, avoided products	Tests whether promising laboratory changes remain beneficial at industrial scale
Duan et al. (2022), full-chain BF slag utilization	TEA	Integrated full-chain utilization vs conventional management	Capital, energy, product revenue, utilization rate	Shows that route ranking depends on whole-chain economics, not unit operation alone

Study / route	Assessment type	Reference alternative / boundary	Dominant decision variables	Critical use in this review
Falsafi et al. (2023), secondary-metallurgy slag	Multi-criteria decision analysis	Competing valorization options	Technical feasibility, environmental performance, economics	Formalizes trade-offs where no single recovery metric is sufficient
Quéheille et al. (2021), nickel-slag-to-cement	Prospective LCA	Emerging product vs incumbent construction route	Scale-up, transport, product substitution	Demonstrates sensitivity of early-stage ranking to assumed industrial context
J. Yang et al. (2026), steel-slag treatments	Comparative life-cycle assessment	Alternative treatment chains	Electricity, transport, grinding, carbonation, displacement credit	Supports conditional rather than universal technology rankings

Note. Author-developed comparison from the cited studies. Functional units and exact boundaries differ among studies; the table therefore emphasizes the decision variables that change technology ranking rather than implying numerical equivalence.

9.4 Slag management under metallurgical decarbonization

System-level decarbonization studies also show that slag strategies interact with the transformation of primary metallurgy. As steelmaking shifts toward scrap-based EAF, DRI, hydrogen, and other lower-carbon routes, both the quantity and chemistry of slag change. The historical assumption that blast-furnace slag will always dominate the cementitious slag supply is therefore weakening, while the need to engineer EAF and secondary-metallurgy slags is increasing (Ehrenberg, 2025; Lv et al., 2026; Sun et al., 2022).

The comparative evidence suggests that no universal hierarchy exists. Life-cycle trade-offs for steel slag treatment can change with electricity mix, transport, grinding, carbonation intensity, and product displacement (J. Yang et al., 2026). Techno-economic assessments likewise depend on local energy and product prices (Duan et al., 2022). The appropriate decision is thus conditional: choose the least intensive intervention that meets the combined metal-recovery, product-quality, environmental, and market objective.

10. CRITICAL SYNTHESIS AND FIVE-GATE INDUSTRIAL FRAMEWORK

10.1 Conditions for genuine value creation

The literature can be reduced to a simple yet demanding proposition: slag upgrading adds value when a controllable transformation yields a separable, marketable benefit without transferring unacceptable cost or hazard to another stream. This sounds obvious, but it excludes many superficially attractive routes to valorization. A process that raises metal recovery but leaves an unstable residue, or a process that makes a high-performance laboratory ceramic from a tiny fraction of slag, may not constitute meaningful industrial upgrading (Pereira, 2026a).

The most convincing examples share five characteristics. First, the value inventory is explicit: recoverable metal, thermal energy, reactive oxides, or a product-quality opportunity is identified before treatment. Second, the controlling mechanism is known well enough to engineer—such as droplet settling after CaO modification, reduction-driven metal formation, phase-specific carbonation, or controlled hot-stage mineral formation (Doschek-Held et al., 2025; Isaksson et al., 2023; Krammer et al., 2026; Liu et al., 2026; Peys et al., 2025). Third, the process contains an effective separation or qualification step rather than assuming that transformation alone creates a product. Fourth, the residual matrix is treated as a co-product with its own specification. Fifth, the route fits a realistic industrial operating window.

The historical titanium UGS route remains conceptually valuable because it embodies the sequence in which impurity removal and mineral transformation are performed to create a feedstock with a defined downstream function (Goso et al., 2022). Modern analogs include modified copper slags, engineered EAF slags, and co-treatment routes that deliberately produce both a metal-rich phase and a usable residual matrix (Liu et al., 2026; G. Wang et al., 2026; Z.-H. Yang et al., 2026).

Industrial evidence also suggests that simpler integrated interventions may outperform more elaborate stand-alone processes. CaO modification linked to settling, hot-stage modification linked to cementitious use, plant flotation of copper slag, and industrial heat recovery all exploit conditions that already exist in the primary process (Isaksson et al., 2026; Isaksson et al., 2023; Pavez et al., 2021; Valderrama et al., 2024; Wu et al., 2023; T. Zhang et al., 2021). By contrast, routes requiring remelting, multiple reagent-

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intensive leaching steps, or specialty products face a higher burden of proof unless they recover particularly valuable metals or address a severe environmental constraint.

10.2 The five-gate industrial screening logic

The proposed five-gate framework therefore treats upgrading as a sequence of decisions rather than a menu of technologies. A slag should pass a value gate, an engineerability gate, a separation-and-safety gate, an integration gate, and a system-performance gate before industrial deployment. This framework is consistent with the direction of recent work on green-steel integration, carbon-negative mineralization, co-treatment, and electric-field process intensification, all of which explicitly couple slag behavior to broader process-system objectives (Kek et al., 2026; X. Wang et al., 2026; Z.-H. Yang et al., 2026; Zhou et al., 2026).

Figure 6 operationalizes the critical synthesis as a sequence of go/no-go decisions. It is positioned here because Sections 3–9 establish the evidence needed to interrogate each gate rather than treating the framework as a stand-alone conceptual diagram.

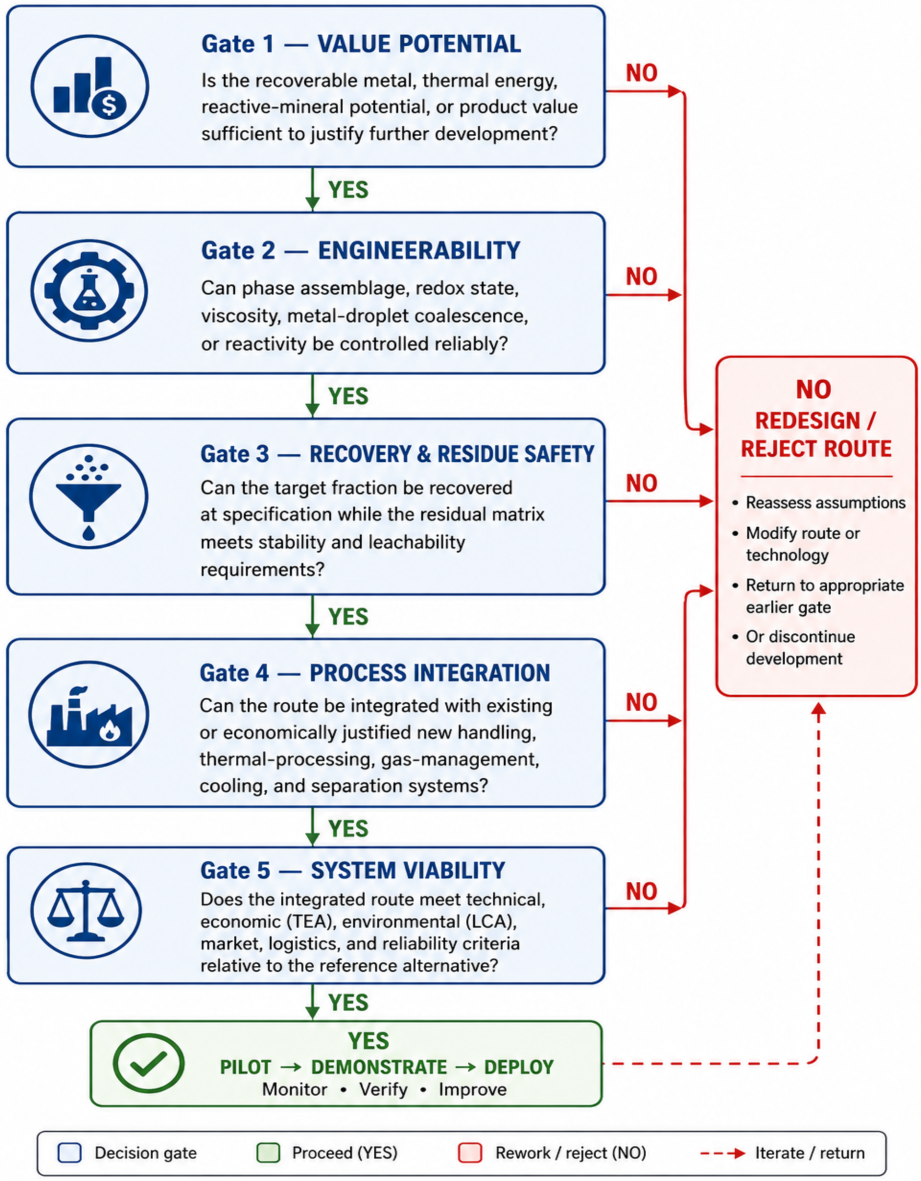

Figure 6. Five-gate decision framework for industrial slag upgrading.

Note. Author-developed synthesis based on Buyle et al. (2021), Duan et al. (2022), Falsafi et al. (2023), Kek et al. (2026), Liu et al. (2026), X. Wang et al. (2026), J. Yang et al. (2026), and Zhou et al. (2026).

10.3 Application of the framework to representative routes

To test whether the five gates discriminate meaningfully among technologies, Table 8 applies the framework to five representative pathways. "Pass" indicates that the reviewed evidence provides a credible answer to the gate; "Conditional" indicates that the route can pass only under site-, feed-, or market-specific conditions; and "Insufficient" indicates that the evidence base remains inadequate for a general industrial conclusion. The exercise is a structured synthesis of evidence rather than a formal scoring model.

Table 8. Five-gate screening of representative slag-upgrading pathways

Representative route	G1 Value	G2 Engineer.	G3 Sep. & safety	G4 Integration	G5 System	Readiness interpretation
Historical / modified UGS	Pass	Pass	Pass	Pass	Conditional	Industrial lineage; product specification remains decisive
Copper-slag flotation	Pass	Pass	Pass	Pass	Conditional	Industrially demonstrated where feed liberation and concentrate economics are favorable
CaO-modified Cu slag + settling	Pass	Pass	Pass	Pass	Conditional	Strong industrial-trial evidence; viscosity, dosing, temperature, and residual-slag value control deployment
Hot-stage EAF/BOF modification	Pass	Conditional	Conditional	Pass	Conditional	Promising pilot/emerging route; furnace capacity and consistent product qualification remain limiting
Carbonation/mineralization	Conditional	Pass	Conditional	Conditional	Conditional	Technically broad, but net carbon benefit and product market are strongly site-dependent

Note. G1 = value inventory; G2 = engineerability; G3 = separation and safety; G4 = integration; G5 = system performance. The classifications synthesize evidence discussed in Sections 3–9 and are not intended as universal numerical TRL assignments.

The case comparison shows why the framework is useful. Copper-slag flotation and UGS-type beneficiation have clear value and product functions, but their deployment still depends on feed and market specifications. CaO modification is strengthened by direct industrial settling evidence, yet its operating window depends on viscosity, temperature, and modifier control. Hot-stage steel-slag modification benefits from integration with sensible heat but remains vulnerable to furnace time and product consistency constraints. Carbonation has a broad mechanistic evidence base, but Gate 5 is highly conditional because net climate benefit depends on grinding, gas preparation, transport, curing, and the displaced product. A route that fails an early gate should therefore not advance merely because a later laboratory performance metric is attractive.

11. RESEARCH GAPS AND FUTURE PERSPECTIVES

11.1 Terminology, reporting, and hot-stage research

The first research gap is terminology and reporting. "Valorization," "recycling," "modification," and "upgrading" are often used interchangeably, which obscures the intensity and purpose of treatment. Future studies should report the untreated state, the applied transformation, the targeted change in property, the post-treatment state, and the final product specification. This would make results more comparable and would align the literature with the increasingly product-oriented view of slag engineering (Fan et al., 2025; Fan et al., 2026).

Second, hot-stage and inline engineering deserve greater emphasis. Many laboratory studies begin with cold, ground slag and therefore ignore the thermal state in which the material actually leaves the furnace. Research on heat recovery, hot modification, additive dissolution, green-steel integration, and industrial smelter concepts indicates that the highest-value future routes may be those designed before cooling (Fernández-González et al., 2024; Halwax et al., 2025; Kek et al., 2026; Voraberger et al., 2026). The challenge is to develop robust sensors, mixing strategies, refractory-compatible reactors, and control models for variable feeds.

11.2 Co-optimization and high-value products

Third, metal recovery and residue valorization should be co-optimized. Future reduction or separation studies should characterize not only metal recovery and grade, but also the mineralogy, leaching, reactivity, and market suitability of the residual slag. This is particularly important for Ti-, Cr-, V-, Mn-, and Fe-bearing systems where the valuable element and the matrix chemistry are tightly coupled (Andersson et al., 2026; Li et al., 2025; Martin-Treceno et al., 2021; Xu et al., 2023).

Fourth, high-value functional applications need stronger evidence of scale and market presence. Catalysts, nanosorbents, and other functional products demonstrate impressive materials chemistry, but industrial relevance depends on reproducibility, contaminant control, regeneration, end-of-life handling, and addressable market size (Kholkina et al., 2020; Kim et al., 2026; F.-P. Wang et al., 2021; Wang et al., 2025). Future work should benchmark slag-derived materials against incumbent products on performance per unit cost and per unit environmental burden, not only on proof-of-concept activity.

11.3 TEA/LCA harmonization, evidence reporting, and changing slag chemistry

Fifth, the evidence base needs harmonized TEA/LCA at earlier stages. Ex-ante life-cycle methods, full-chain techno-economics, and comparative treatment assessments are beginning to close this gap, but assumptions on energy mix, avoided products, slag transport, plant availability, and coproduct credit remain inconsistent (Buyle et al., 2021; Duan et al., 2022; J. Yang et al., 2026). A common minimum dataset would substantially improve technology screening. Future studies should report a minimum industrialization dataset comprising feed mineralogy and variability, mass and energy balances, reagent and reductant demand, recovery and product grade, residual matrix mineralogy and leaching, throughput or residence time, utility requirements, and the system boundary used for economic or environmental claims (Pereira, 2026b).

Finally, the transition to lower-carbon metallurgy will change the slags themselves. Scrap-rich EAF production, hydrogen-based ironmaking, molten oxide electrolysis, and new circular smelting loops will alter FeO, CaO, MgO, Al_2O_3, trace-element load, and thermal integration opportunities. Slag engineering should therefore be developed alongside primary-process innovation rather than treated as a downstream waste problem (Andersson et al., 2026; Kek et al., 2026; Voraberger et al., 2026; Zhou et al., 2026).

The evidence map also identifies a research-balance issue. Steelmaking slags dominate the recent literature, while Ti-bearing and Ni/ferronickel upgrading have much smaller clusters of recent evidence. Future cross-system work should therefore avoid assuming that findings from Ca-rich steel slags transfer directly to iron-silicate, pyroxene-rich, or Ti-rich systems. Comparable reporting across slag families would enable stronger future quantitative synthesis.

12. CONCLUSIONS

Metallurgical slag upgrading is best understood as a value-directed engineering discipline rather than as a synonym for slag reuse. The historical UGS lineage in titanium metallurgy demonstrates the central logic: a slag becomes an upgraded feedstock only when its mineralogy and impurity distribution are deliberately transformed, and the resulting product satisfies a defined downstream specification. Modern slag engineering extends that logic to metal recovery, controlled cooling, chemical modification, redox treatment, physical separation, carbonation, electrochemical processing, heat recovery, and integrated product design.

The descriptive mapping of the recent evidence base shows substantial imbalance among slag families and between laboratory and industrial evidence. Steelmaking studies dominate the corpus, whereas explicit industrial or industrial-scale demonstrations are concentrated in a smaller set of copper-slag, hot-stage steel, heat-recovery, and mineralization pathways. Representative quantitative benchmarks further show that technology performance cannot be reduced to a single recovery number: viscosity and droplet settling, concentrate grade and throughput, feedstock impurity specifications, recoverable heat, residual matrix quality, and system boundaries define success differently across routes.

The revised five-gate framework converts these findings into a practical industrial screen. A credible route must demonstrate a sufficiently large inventory value, an engineerable transformation, effective separation with an environmentally acceptable residual matrix, realistic integration with existing plant infrastructure, and system-level performance that remains favorable when economics, life-cycle effects, product markets, logistics, and reliability are considered. Process intensity should therefore be proportional to the value or risk reduction created. The most transferable conclusion is not a universal treatment recipe, but a requirement for site-specific co-design of metallurgy, mineral processing, materials performance, environmental control, and industrial integration.

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Data availability

No new experimental data were generated. The evidence base consists of the published sources listed in the References section.

Author contributions

Conceptualization, literature curation, critical analysis, synthesis, visualization, and manuscript preparation were performed by the author.

REFERENCES

1. Andersson, A., Isaksson, J., Lennartsson, A., & Engström, F. (2024). Insights into the valorization of electric arc furnace slags as supplementary cementitious materials. *Journal of Sustainable Metallurgy, 10*(1), 96–109. https://doi.org/10.1007/s40831-023-00778-y
2. Andersson, A., Lee, M. J., Park, S. H., Hwang, S. M., Engström, F., & Park, J. H. (2026). The incorporation of VO_x in the glass structure of electric arc furnace slag and its implication on slag valorization. *Journal of Sustainable Metallurgy, 12*(4), 3785–3801. https://doi.org/10.1007/s40831-026-01534-8
3. Ashrit, S., Sarkar, S., Chatti, R. V., Sarkar, C., & Sarkar, S. (2020). Nonmetallic LD slag fines—Opportunities by invoking chemistry. *Ironmaking & Steelmaking, 47*(8), 903–907. https://doi.org/10.1080/03019233.2019.1641679
4. Baras, A., Li, J., Ni, W., Hussain, Z., & Hitch, M. (2023). Evaluation of potential factors affecting steel slag carbonation. *Processes, 11*(9), Article 2590. https://doi.org/10.3390/pr11092590
5. Barati, M., & Jahanshahi, S. (2020). Granulation and heat recovery from metallurgical slags. *Journal of Sustainable Metallurgy, 6*(2), 191–206. https://doi.org/10.1007/s40831-019-00256-4
6. Binnemans, K., Jones, P. T., Manjón Fernández, Á., & Masaguer Torres, V. (2020). Hydrometallurgical processes for the recovery of metals from steel industry by-products: A critical review. *Journal of Sustainable Metallurgy, 6*(4), 505–540. https://doi.org/10.1007/s40831-020-00306-2
7. Blenau, L. W., Sander, S. A. H., Fuhrmann, S., & Charitos, A. (2023). Holistic valorization of fayalitic slag to pig iron and glass fibers. *Journal of Cleaner Production, 418*, Article 137990. https://doi.org/10.1016/j.jclepro.2023.137990
8. Bonfante, F., Ferrara, G., Humbert, P., Garufi, D., Tulliani, J.-M., & Palmero, P. (2025). Direct aqueous carbonation of electric arc furnace slag: Process optimisation through experimental design. *Materials and Structures, 58*(4), Article 127. https://doi.org/10.1617/s11527-025-02661-.
9. Borowiec, K., Grau, A. E., Gueguin, M., & Turgeon, J.-F. (1998). *Method to upgrade titania slag and resulting product* (U.S. Patent No. 5,830,420). U.S. Patent and Trademark Office. https://patents.google.com/patent/US5830420A/en
10. Branca, T. A., Colla, V., Algermissen, D., Granbom, H., Martini, U., Morillon, A., Pietruck, R., & Rosendahl, S. (2020). Reuse and recycling of by-products in the steel sector: Recent achievements paving the way to circular economy and industrial symbiosis in Europe. *Metals, 10*(3), Article 345. https://doi.org/10.3390/met10030345
11. Bullerjahn, F., & Bolte, G. (2022). Composition of the reactivity of engineered slags from bauxite residue and steel slag smelting and use as SCM for Portland cement. *Construction and Building Materials, 321*, Article 126331. https://doi.org/10.1016/j.conbuildmat.2022.126331
12. Buyle, M., Maes, B., Van Passel, S., Boonen, K., Vercalsteren, A., & Audenaert, A. (2021). Ex-ante LCA of emerging carbon steel slag treatment technologies: Fast forwarding lab observations to industrial-scale production. *Journal of Cleaner Production, 313*, Article 127921. https://doi.org/10.1016/j.jclepro.2021.127921
13. Cao, S.-Y., Du, C.-M., Liu, J.-X., Wei, Y.-B., & Wang, Z.-J. (2025). Effective detoxification of the Cr-bearing stainless-steel slag by cooling control and self-wrapped spinel precipitation. *Journal of Environmental Chemical Engineering, 13*(5), Article 119095. https://doi.org/10.1016/j.jece.2025.119095

14. Carvalho, V. R., Costa, L. C. B., da Fonseca Elói, F. P., da Silva Bezerra, A. C., de Carvalho, J. M. F., & Peixoto, R. A. F. (2023). Performance of low-energy steel slag powders as supplementary cementitious materials. *Construction and Building Materials, 392*, Article 131888. https://doi.org/10.1016/j.conbuildmat.2023.131888
15. Chandel, S. S., Lavakumar, A., Randhawa, N. S., & Singh, P. K. (2025). Unique hot stage modification technique to enhance cementitious properties of electric arc furnace steel slag. *Journal of Environmental Management, 376*, Article 124398. https://doi.org/10.1016/j.jenvman.2025.124398
16. Chen, S., Tan, W., Fan, Y., Zhu, J., Zhao, S., Wu, J., Ding, C., Guo, Z., Guan, X., Wang, X., & Zhang, Z. (2025). Enhancing copper recovery from smelting slag: Multiscale kinetic control of nucleation and scalable application strategies. *Separation and Purification Technology, 379*, Article 135113. https://doi.org/10.1016/j.seppur.2025.135113
17. Cheng, J., Yu, L., Zhang, B., Liu, Z., Zhang, Z., Li, J., Li, S., & Feng, P. (2026). Synergistic smelting of copper slag and spent ternary lithium batteries for Fe–Ni–Co alloy preparation: Iron capture and alloy formation mechanism. *Journal of Sustainable Metallurgy*. Advance online publication. https://doi.org/10.1007/s40831-026-01597-7
18. Deng, L., Yao, B., Lu, W., Zhang, M., Li, H., Chen, H., Zhao, M., Du, Y., Zhang, M., Ma, Y., & Wang, W. (2022). Effect of SiO_2/Al_2O_3 ratio on the crystallization and heavy metal immobilization of glass ceramics derived from stainless steel slag. *Journal of Non-Crystalline Solids, 593*, Article 121770. https://doi.org/10.1016/j.jnoncrysol.2022.121770.
19. Di Maria, A., & Van Acker, K. (2021). Consequential life cycle assessment to promote the recycling of metallurgic slag as new construction material. In P. Singh, P. Verma, D. Perrotti, & K. K. Srivastava (Eds.), *Environmental sustainability and economy* (pp. 247–271). Elsevier. https://doi.org/10.1016/B978-0-12-822188-4.00017-8
20. Doschek-Held, K., Krammer, A. C., Steindl, F. R., Gatschlhofer, C., Raonic, Z., & Wohlmuth, D. (2025). Treatment of metallurgical residues by chemical modification, reduction, and phase modification for metal recovery and slag utilization. *Minerals, 15*(4), Article 408. https://doi.org/10.3390/min15040408
21. Duan, W., Wu, Q., Li, P., & Cheng, P. (2022). Techno-economic analysis of a novel full-chain blast furnace slag utilization system. *Energy, 242*, Article 123049. https://doi.org/10.1016/j.energy.2021.123049
22. Ehrenberg, A. (2025). The steelmaking transformation process and its consequences for slag utilization. *Steel Research International, 96*(5), Article 2400234. https://doi.org/10.1002/srin.202400234
23. Falsafi, M., Terkaj, W., Guzzon, M., Malfa, E., Fornasiero, R., & Tolio, T. (2023). Assessment of valorisation opportunities for secondary metallurgy slag through multi-criteria decision making. *Journal of Cleaner Production, 402*, Article 136838. https://doi.org/10.1016/j.jclepro.2023.136838
24. Fan, Z.-Y., Wang, L., Zhang, R.-Y., Wang, Y.-Y., Zhang, T.-A., Wang, X.-J., Pan, J.-X., Li, J.-D., Li, W.-J., & Ren, J.-W. (2025). Research on the current development status and competitive trends of steel slag treatment and utilization technologies: Analysis from the perspective of global patent. *Journal of Sustainable Metallurgy, 11*(4), 3388–3406. https://doi.org/10.1007/s40831-025-01274-1
25. Fan, Z.-Y., Wang, L., Zhang, R.-Y., Wang, Y.-Y., Zhang, T.-A., Zhao, X.-X., Wang, X.-J., Li, J.-D., & Li, W.-J. (2026). From waste to resource: Multiscale analysis and high-value utilization strategies for steel slag. *Powder Technology, 479*, Article 122593. https://doi.org/10.1016/j.powtec.2026.122593
26. Fernández-González, D., Piñuela-Noval, J., Gómez-Rodríguez, C., Fernández Valdés, A., & Verdeja González, L. F. (2024). Implications of renewable energy sources in metallurgy: Utilization of concentrated solar energy in recycling metallurgical wastes. *Applied Thermal Engineering, 250*, Article 123511. https://doi.org/10.1016/j.applthermaleng.2024.123511
27. Filippou, D., & Hudon, G. (2020). Minerals, slags, and other feedstock for the production of titanium metal. In Z. Z. Fang, F. H. Froes, & Y. Zhang (Eds.), *Extractive metallurgy of titanium: Conventional and recent advances in extraction and production of titanium metal* (pp. 19–45). Elsevier. https://doi.org/10.1016/B978-0-12-817200-1.00003-X
28. Gao, X., Chen, Z., Shi, J., Taskinen, P., & Jokilaakso, A. (2020). Effect of cooling rate and slag modification on the copper matte in smelting slag. *Mining, Metallurgy & Exploration, 37*(5), 1593–1601. https://doi.org/10.1007/s42461-020-00274-x.
29. Goso, X., Petersen, J., Tangstad, M., & Safarian, J. (2022). Beneficiation of fluxed titaniferous slag to a marketable titania product using the modified upgraded slag process. *Mineral Processing and Extractive Metallurgy, 131*(3), 239–249. https://doi.org/10.1080/25726641.2021.1959882

30. Grengg, C., Rudic, O., Saade, M. R. M., Steindl, F. R., Wilkening, M., Jodlbauer, A., Zoegl, I., Wohlmuth, D., & Mittermayr, F. (2024). Alkali activated steel slag–oil composites: Towards resource efficiency and CO_2 neutrality. *Cement and Concrete Research, 186*, Article 107678. https://doi.org/10.1016/j.cemconres.2024.107678
31. Gu, X., Yang, B., Li, Z., Hu, Z., Liu, J., & Wang, Q. (2026). Leaching behavior and hydration characteristics of phosphogypsum-based supersulfated cement for heavy metal stabilization in metallurgical slags. *Journal of Sustainable Metallurgy, 12*(3), 3027–3043. https://doi.org/10.1007/s40831-026-01498-9
32. Guéguin, M., & Cardarelli, F. (2007). Chemistry and mineralogy of titania-rich slags. Part 1—Hemo-ilmenite, sulphate, and upgraded titania slags. *Mineral Processing and Extractive Metallurgy Review, 28*(1), 1–58. https://doi.org/10.1080/08827500600564242
33. Halwax, A., Marschall, I., Schlemmer, N., Kek, F., Eisbacher-Lubensky, J., & Weiß, C. (2025). Experimental investigation of additive dissolution behavior in slags and analysis of physical and electrochemical properties. *BHM Berg- und Hüttenmännische Monatshefte, 170*(7), 415–421. https://doi.org/10.1007/s00501-025-01591-8
34. Hanke, G., Antrekowitsch, J., Castro, F., & Krug, H. (2022). Maximizing the efficiency of by-product treatment by multi-metal recovery and slag valorization. In A. Lazou, K. Daehn, C. Fleuriault, M. Gökelma, E. Olivetti, & C. Meskers (Eds.), *REWAS 2022: Developing tomorrow's technical cycles* (Vol. I, pp. 201–211). Springer. https://doi.org/10.1007/978-3-030-92563-5_22
35. Hao, J., Dou, Z., Wan, X., Qi, S., Wang, K., & Zhang, T.-A. (2024). High-value terminal treatment: Utilizing copper slag heat in the manufacture of copper-containing weathering steel. *Journal of Cleaner Production, 477*, Article 143829. https://doi.org/10.1016/j.jclepro.2024.143829
36. Hao, S., Luo, G., Wang, L., An, S., Chai, Y., & Song, W. (2024). Tempering and modification of basic oxygen furnace slag with blast furnace slag: Mineral phase transformations and cementitious material enrichment mechanisms. *Case Studies in Construction Materials, 21*, Article e03803. https://doi.org/10.1016/j.cscm.2024.e03803
37. Huang, Y., Li, Y., Cheng, Z., & Feng, W. (2025). Hot modification of silicomanganese slag in its crystallization and viscosity properties for preparation of cast stone. *Ceramics, 8*(1), Article 22. https://doi.org/10.3390/ceramics8010022
38. Huang, Y., Li, Y., Zhou, Z., & Cheng, Z. (2025). A novel process for low-cost preparation of large-volume cast stone from molten silicomanganese slag. *Construction and Building Materials, 473*, Article 141063. https://doi.org/10.1016/j.conbuildmat.2025.141063.
39. Huang, Y., Xiao, Z., Li, Y., Pan, S., & Cang, D. (2026). Segregation inhibition and performance enhancement of low carbon large-volume cast stone from molten silicomanganese slag. *Waste Disposal & Sustainable Energy*. Advance online publication. https://doi.org/10.1007/s42768-026-00301-5
40. Isaksson, J., Andersson, A., Lennartsson, A., Roos, Å., & Engström, F. (2026). Assessing the performance of industrially CaO-modified copper slag as a supplementary cementitious material. *Journal of Sustainable Metallurgy, 12*(4), 3626–3639. https://doi.org/10.1007/s40831-026-01521-z
41. Isaksson, J., Andersson, A., Vikström, T., Lennartsson, A., & Samuelsson, C. (2023). Improved settling mechanisms of an industrial copper smelting slag by CaO modification. *Journal of Sustainable Metallurgy, 9*(3), 1378–1389. https://doi.org/10.1007/s40831-023-00733-x
42. Jacob, L. (2024). Ladle furnace slag: Synthesis, properties, and applications. *ChemBioEng Reviews, 11*(1), 60–78. https://doi.org/10.1002/cben.202300024
43. Kek, F., Zettl, K.-M., Kollmann, T., Tanasic, N., Stahl, P., & Lin, M. (2026). Green steel initiatives supported by CERO waste refractory concept, enhanced slag engineering and using circular metallurgical additives. *BHM Berg- und Hüttenmännische Monatshefte, 171*(1), 13–20. https://doi.org/10.1007/s00501-025-01685-3
44. Kero Andertun, J., Vikström, T., Peltola, P., Samuelsson, C., & Engström, F. (2021). Characterisation and leaching behavior of CaO-modified iron-silicate slag produced in laboratory and industrial scales. *Canadian Metallurgical Quarterly, 60*(4), 294–305. https://doi.org/10.1080/00084433.2021.2016346
45. Kholkina, E., Kumar, N., Ohra-aho, T., Lehtonen, J., Lindfors, C., Perula, M., Peltonen, J., Salonen, J., & Murzin, D. Y. (2020). Transformation of industrial steel slag with different structure-modifying agents for synthesis of catalysts. *Catalysis Today, 355*, 768–780. https://doi.org/10.1016/j.cattod.2019.04.033

46. Kim, G., & Sohn, I. (2023). In-situ observation and crystallization kinetics during the solidification of Cr-containing stainless steel slags. *Journal of Materials Research and Technology, 25*, 7273–7291. https://doi.org/10.1016/j.jmrt.2023.07.106
47. Kim, S.-J., Zhang, L., He, B., & Kang, S.-S. (2026). Closing the loop: A sustainable resource management strategy for valorizing steel slag into nanosorbents for water remediation. *ACS Sustainable Resource Management, 3*(4), 1031–1042. https://doi.org/10.1021/acssusresmgt.5c00569
48. Kinnunen, P., Mäkinen, J., Salo, M., Soth, R., & Komnitsas, K. (2020). Efficiency of chemical and biological leaching of copper slag for the recovery of metals and valorisation of the leach residue as raw material in cement production. *Minerals, 10*(8), Article 654. https://doi.org/10.3390/min10080654
49. Krammer, A., Doschek-Held, K., Gatschlhofer, C., Steindl, F. R., Presoly, P., & Raonic, Z. (2026). Optimisation of metal recovery from metallurgical residues through carbothermal reduction: Experimental and thermodynamic investigation. *Circular Economy and Sustainability, 6*(4), Article 328. https://doi.org/10.1007/s43615-026-01058-z.
50. Kuang, B., Tan, C., Li, F., Hu, J., Dou, Z., Yu, Y., Gao, H., & Wang, H. (2026). A novel method for cleaning molten copper slag and efficiently recovering copper resources through reduction modification. *Process Safety and Environmental Protection, 210*, Article 108649. https://doi.org/10.1016/j.psep.2026.108649
51. Kuanyshev, M., Sariyev, O., Aitkenov, N., Tukashev, Z., Kelamanov, B., Yerzhanov, A., Zhabalova, G., & Abilberikova, A. (2026). Stabilization of self-disintegrating refined ferrochrome slags using desulfurized borate ore from the Inder deposit: A comparative study with colemanite. *Materials, 19*(14), Article 2947. https://doi.org/10.3390/ma19142947
52. Kudyba, A., & Safarian, J. (2022). Manganese and aluminium recovery from ferromanganese slag and Al white dross by a high temperature smelting-reduction process. *Materials, 15*(2), Article 405. https://doi.org/10.3390/ma15020405
53. Kudyba, A., Akhtar, S., Johansen, I., & Safarian, J. (2021). Aluminothermic reduction of manganese oxide from selected MnO-containing slags. *Materials, 14*(2), Article 356. https://doi.org/10.3390/ma14020356
54. Lancellotti, I., Piccolo, F., Traven, K., Češnovar, M., Ducman, V., & Leonelli, C. (2021). Alkali activation of metallurgical slags: Reactivity, chemical behavior, and environmental assessment. *Materials, 14*(3), Article 639. https://doi.org/10.3390/ma14030639
55. Lee, J., Ryu, K. H., Ha, H. Y., Jung, K. D., & Lee, J. H. (2020). Techno-economic and environmental evaluation of nano calcium carbonate production utilizing the steel slag. *Journal of CO_2 Utilization, 37*, 113–121. https://doi.org/10.1016/j.jcou.2019.12.005
56. Li, C., Du, P., Zhang, J., Zhao, S., Gao, M., Wang, Q., Tian, T., Li, L., & Long, Y. (2025). Advances in integrated extraction of valuable components from Ti-bearing slag. *Metals, 15*(10), Article 1080. https://doi.org/10.3390/met15101080
57. Li, Z., Xing, Y., Ma, M., Su, W., Cui, Y., Tian, J., & Fei, F. (2024). Towards the co-benefits of carbon capture, utilization and sequestration: A life cycle assessment study for steel slag disposal. *Journal of Cleaner Production, 443*, Article 141166. https://doi.org/10.1016/j.jclepro.2024.141166
58. Lin, Y., Yan, B., Shu, Q., & Fabritius, T. (2021). Synergetic valorization of basic oxygen furnace slag and stone coal: Metal recovery and preparation of glass-ceramics. *Waste Management, 135*, 158–166. https://doi.org/10.1016/j.wasman.2021.08.044
59. Liu, S., Xu, L., & Chen, M. (2026). Iron recovery and valorization of EAF slag by online smelting reduction via Al_2O_3 modification. *JOM, 78*(7), 6024–6038. https://doi.org/10.1007/s11837-026-08414-2
60. Liu, X., & Bao, Y.-P. (2024). Separation and extraction of iron resources from hazardous electric arc furnace (EAF) steel slag: Aggregation of Fe-rich layers, magnetic separation, powder characterization. *Process Safety and Environmental Protection, 190*, 420–428. https://doi.org/10.1016/j.psep.2024.08.064.
61. Liu, X., Wang, D.-Z., Li, Z.-W., Ouyang, W., Bao, Y.-P., & Gu, C. (2023). Efficient separation of iron elements from steel slag based on magnetic separation process. *Journal of Materials Research and Technology, 23*, 2362–2370. https://doi.org/10.1016/j.jmrt.2023.01.186
62. Liu, X., Wu, P., Liu, X., Zhang, Z., & Ai, X. (2024). The utilization of carbonated steel slag as a supplementary cementitious material in cement. *Materials, 17*(18), Article 4574. https://doi.org/10.3390/ma17184574

63. Lv, Y., Wu, J., Han, Z., Xiang, Y., Sun, Z., Liu, X., Wang, H., Ren, W., Zhu, X., & Liao, Q. (2026). Harnessing the heat and material potential in steel slag to decarbonize China's steel industry. *Carbon Neutrality, 5*, Article 25. https://doi.org/10.1007/s43979-026-00179-6
64. Machini, B., Simões, D., Humbert, P., António, J., & Almeida, J. (2026). A comparative evaluation of three valorisation pathways for waste electric arc furnace slag to improve its use as an eco-logical binder. *Recycling, 11*(2), Article 25. https://doi.org/10.3390/recycling11020025
65. Martin-Treceno, S., Hughes, T., Weaver, N., Marshall, A. T., Watson, M. J., & Bishop, C. M. (2021). Electrochemical study on the reduction of Si and Ti from molten TiO_2–SiO_2–Al_2O_3–MgO–CaO slag. *Journal of The Electrochemical Society, 168*(6), Article 062502. https://doi.org/10.1149/1945-7111/ac0301
66. Matsuura, H., Yang, X., Li, G., Yuan, Z., & Tsukihashi, F. (2022). Recycling of ironmaking and steelmaking slags in Japan and China. *International Journal of Minerals, Metallurgy and Materials, 29*(4), 739–749. https://doi.org/10.1007/s12613-021-2400-5
67. Menad, N.-E., Kana, N., Seron, A., & Kanari, N. (2021). New EAF slag characterization methodology for strategic metal recovery. *Materials, 14*(6), Article 1513. https://doi.org/10.3390/ma14061513
68. Pavez, O., Herrera, P., González, M., & Rivera, O. (2021). Copper recovery through smelter slag flotation in Atacama, Chile: An industrial case study. *Ingeniería e Investigación, 41*(1), Article e84162. https://doi.org/10.15446/ing.investig.v41n1.84162.
69. Pereira, A. C. (2026a). Secondary aluminum dross and salt slag treatment: A critical review of integrated value recovery, risk control, and industrial readiness. *International Journal of Current Science Research and Review, 9*(8), 4428–4462. https://doi.org/10.47191/ijcsrr/V9-i8-23.
70. Pereira, A. C. (2026b). Scrap selection and charge design for foundry alloys: A critical review of classification criteria, metallurgical constraints, and industrial practices. *Journal International Review of Research Studies, 1*(10), 1–52. https://doi.org/10.66104/f577ny49
71. Peys, A., Martins, N. P., Araujo, F. P., Komnitsas, K., & Nielsen, P. (2025). High-temperature slag engineering in pursuit of effective mineral carbonation of pyroxene-rich ferronickel slag. Journal of CO_2 Utilization, 95, Article 103077. https://doi.org/10.1016/j.jcou.2025.103077
72. Pistorius, P. C., & Coetzee, C. (2003). Physicochemical aspects of titanium slag production and solidification. Metallurgical and Materials Transactions B, 34(5), 581–588. https://doi.org/10.1007/s11663-003-0027-8
73. Quéheille, E., Dauvergne, M., & Ventura, A. (2021). Prospective life cycle assessment at early stage of product development: Application to nickel slag valorization into cement for the construction sector. Frontiers in Built Environment, 7, Article 743948. https://doi.org/10.3389/fbuil.2021.743948
74. Ragipani, R., Bhattacharya, S., & Suresh, A. K. (2021). A review on steel slag valorisation via mineral carbonation. Reaction Chemistry & Engineering, 6(7), 1152–1178. https://doi.org/10.1039/D1RE00035G
75. Rieger, J., Colla, V., Matino, I., Branca, T. A., Stubbe, G., Panizza, A., Brondi, C., Falsafi, M., Hage, J., Wang, X., Voraberger, B., Fenzl, T., Masaguer, V., Faraci, E. L., Di Sante, L., Cirilli, F., Loose, F., Thaler, C., Soto, A., … Snaet, D. (2021). Residue valorization in the iron and steel industries: Sustainable solutions for a cleaner and more competitive future Europe. Metals, 11(8), Article 1202. https://doi.org/10.3390/met11081202
76. Samanta, N. S., Das, P. P., Dhara, S., & Purkait, M. K. (2023). An overview of precious metal recovery from steel industry slag: Recovery strategy and utilization. Industrial & Engineering Chemistry Research, 62(23), 9006–9031. https://doi.org/10.1021/acs.iecr.3c00604
77. Schneider, J., Adam, C., Adamczyk, B., Algermissen, D., Ebert, D., Ehrenberg, A., Gerlach, J., Mayer, F., & Schraut, K. (2026). Usage of BOF slag and next generation EAF slag in the cement industry. Journal of Sustainable Metallurgy, 12, 3498–3517. https://doi.org/10.1007/s40831-026-01481-4
78. Shang, W., Peng, Z., Xu, F., Tang, H., Rao, M., Li, G., & Jiang, T. (2021). Preparation of enstatite-spinel based glass-ceramics by co-utilization of ferronickel slag and coal fly ash. Ceramics International, 47(20), 29400–29409. https://doi.org/10.1016/j.ceramint.2021.07.108

79. Shin, S., & Kim, M.-J. (2026). Integrated valorization of blast furnace slag for dual production of zeolite X and $CaCO_3$. Chemical Engineering Journal Advances, 26, Article 101192. https://doi.org/10.1016/j.ceja.2026.101192
80. Srivastava, S., Snellings, R., Nielsen, P., & Cool, P. (2022). Accelerated carbonation of ferrous and non-ferrous slags to produce clinker-free carbonate-bonded blocks: Synergetic reduction in environmental leaching. Construction and Building Materials, 348, Article 128630. https://doi.org/10.1016/j.conbuildmat.2022.128630
81. Stabile, P., Vetere, F., Giuliani, L., Siligardi, C., Mugoni, C., Nazzari, M., & Iezzi, G. (2025). Fabrication of new glass–ceramic materials from float glass and slag waste by modulation of the cooling rate. Waste Management, 208, Article 115141. https://doi.org/10.1016/j.wasman.2025.115141
82. Stefanini, L., Walkley, B., & Provis, J. L. (2024). Basic oxygen furnace (BOF) slag as an additive in sodium carbonate-activated slag cements. Materials and Structures, 57, Article 153. https://doi.org/10.1617/s11527-024-02425-8
83. Sui, Z., Lou, T., & Li, L. (2026). Selective precipitating and separating for utilization of metallurgical slag. Springer Singapore. https://doi.org/10.1007/978-981-96-8410-6.
84. Sukurov, B., Kvyatkovskiy, S., Kozhakhmetov, S., Semenova, A., Dyussebekova, M., & Kvyatkovskaya, M. (2024). Structural changes in copper slags during slow cooling. Metals, 14(10), Article 1187. https://doi.org/10.3390/met14101187
85. Sun, Y., Tian, S., Ciais, P., Zeng, Z., Meng, J., & Zhang, Z. (2022). Decarbonising the iron and steel sector for a 2 °C target using inherent waste streams. Nature Communications, 13, Article 297. https://doi.org/10.1038/s41467-021-27770-y
86. Tzevelekou, T., Lampropoulou, P., Giannakopoulou, P. P., Rogkala, A., Koutsovitis, P., Koukouzas, N., & Petrounias, P. (2020). Valorization of slags produced by smelting of metallurgical dusts and lateritic ore fines in manufacturing of slag cements. Applied Sciences, 10(13), Article 4670. https://doi.org/10.3390/app10134670
87. Valderrama, L., Tapia, J., Pavez, O., Santander, M., Rivera, V., & González, M. (2024). Recovery of copper from slags through flotation at the Hernán Videla Lira Smelter. Minerals, 14(12), Article 1228. https://doi.org/10.3390/min14121228
88. Vollbrecht, M., Pramanik, K., Colombi Ciacchi, L., & Mädler, L. (2024). Investigating the compositional space of gas-phase synthesized fayalitic model slags aiming at cobalt recovery. Journal of Sustainable Metallurgy, 10(3), 1634–1648. https://doi.org/10.1007/s40831-024-00888-1
89. Voraberger, B., Wimmer, G., Pfeiffer, A., Pastucha, K., & Millner, R. (2026). Smelter to close the raw material gap in green steel production. Metallurgical Research & Technology, 123(2), Article 218. https://doi.org/10.1051/metal/2026015
90. Wang, F.-P., Liu, T.-J., Cai, S., Gao, D., Yu, Q., Wang, X.-M., Wang, Y.-T., Zeng, Y.-N., & Li, J.-G. (2021). A review of modified steel slag application in catalytic pyrolysis, organic degradation, electrocatalysis, photocatalysis, transesterification and carbon capture and storage. Applied Sciences, 11(10), Article 4539. https://doi.org/10.3390/app11104539
91. Wang, G., Yu, Q., Shen, Q., Deng, Y., & Feng, Y. (2026). A new copper slag treatment process: Oxidative modification–molten chlorination. JOM, 78(5), 4500–4514. https://doi.org/10.1007/s11837-026-08158-z
92. Wang, J., Guo, Q., Gao, L., & He, Z. (2025). Microwave-driven upcycling of steel slag for SO_2/NO_x co-adsorption via mineral phase reconstruction technology. Separation and Purification Technology, 377, Article 134396. https://doi.org/10.1016/j.seppur.2025.134396
93. Wang, X., Huo, X., Yi, G., Li, H., Guo, M., & Zhang, M. (2026). Carbon-negative mineralization of steel slag via LKD-enhanced in-situ utilization of rotary kiln flue gas: Mechanisms, industrial trials, and life cycle assessment. Chemical Engineering Journal. Advance online publication. https://doi.org/10.1016/j.cej.2026.179907.
94. Wang, Y.-J., Tao, M.-J., Li, J.-G., Zeng, Y.-N., Qin, S., & Liu, S.-H. (2021). Carbonation of EAF stainless steel slag and its effect on chromium leaching characteristics. Crystals, 11(12), Article 1498. https://doi.org/10.3390/cryst11121498
95. Wang, Y.-J., Zeng, Y.-N., Li, J.-G., & Gao, Z.-Y. (2021). Leaching characteristics and mineralogical control of chromium in electric-arc-furnace stainless-steel slag. Materiali in tehnologije, 55(1), 127–133. https://doi.org/10.17222/mit.2020.156
96. Wang, Y.-J., Zeng, Y.-N., Li, J.-G., & Zhang, Y.-Z. (2020). Cementitious behavior of argon oxygen decarburization stainless steel slag and its stabilization on chromium. Crystals, 10(10), Article 876. https://doi.org/10.3390/cryst10100876
97. Wu, J., Tan, Y., Li, P., Wang, H., Zhu, X., & Liao, Q. (2022). Centrifugal-granulation-assisted thermal energy recovery towards low-carbon blast furnace slag treatment: State of the art and future challenges. Applied Energy, 325, Article 119835. https://doi.org/10.1016/j.apenergy.2022.119835

98. Wu, J., Wang, H., Zhu, X., & Liao, Q. (2023). Exploiting the molten slag to decarbonize iron and steel industry: Feasibility analysis of centrifugal granulation-assisted thermal energy recovery system beyond pilot scale. Steel Research International, 94(5), Article 2200300. https://doi.org/10.1002/srin.202200300
99. Xu, J., Liu, M., Ma, G., Zheng, D., Zhang, X., & Hou, Y. (2023). Valuable recovery technology and resource utilization of chromium-containing metallurgical dust and slag: A review. Metals, 13(10), Article 1768. https://doi.org/10.3390/met13101768
100. Yang, J., Wang, H., Du, Y., Wang, H., Jiao, L., Yang, S., Xing, Y., & Ma, H. (2026). Life-cycle environmental trade-offs of steel slag treatment processes: A comparative assessment with process-level drivers. Processes, 14(12), Article 1871. https://doi.org/10.3390/pr14121871
101. Yang, P., Ma, G., Liu, X., Lv, G., Wang, B., Yang, S., Chen, X., Yang, B., & Wu, Z. (2024). Design and simulation of a new carbonation device with both steel slag modification and carbon sequestration functions. International Journal of Heat and Fluid Flow, 110, Article 109628. https://doi.org/10.1016/j.ijheatfluidflow.2024.109628
102. Yang, Z.-H., Du, C.-M., Yu, Y.-H., Feng, Y., & Huo, X. (2026). Co-treatment of steelmaking slag and copper slag for efficient separation of P and Si and recycling of Fe-rich residue. Journal of Environmental Chemical Engineering, 14(4), Article 123328. https://doi.org/10.1016/j.jece.2026.123328
103. Yu, Y.-H., Du, C.-M., Yu, J.-K., & Yang, X. (2022). Effect of BOF slag modification on the dissolution behavior of phosphorus from practical dephosphorization slag. Metallurgical and Materials Transactions B, 53(6), 3635–3647. https://doi.org/10.1007/s11663-022-02626-y
104. Zhang, C., Wang, N., & Chen, M. (2021). Hot slag modification with mechanical stirring: Motion and dispersion characteristic of modifier particle. ISIJ International, 61(11), 2754–2764. https://doi.org/10.2355/isijinternational.ISIJINT-2021-220
105. Zhang, C., Wang, N., & Chen, M. (2022). Heat transfer characteristics of hot slag modification in a mechanically agitated slag pot. Steel Research International, 93(9), Article 2200116. https://doi.org/10.1002/srin.202200116
106. Zhang, L., Blanpain, B., Guo, M., & Malfliet, A. (2023). In-situ electrical conductivity monitoring of slag solidification during continuous cooling for slag recycling. Waste Management, 161, 234–244. https://doi.org/10.1016/j.wasman.2023.02.015
107. Zhang, T., Qiu, G., Wang, H., Guo, M., Cheng, F., & Zhang, M. (2021). In-suit industrial tests of the highly efficient recovery of waste heat and reutilization of the hot steel slag. ACS Sustainable Chemistry & Engineering, 9(10), 3955–3962. https://doi.org/10.1021/acssuschemeng.1c00081
108. Zhao, Q., Liu, K., Sun, L., Liu, C., Jiang, M., Saxén, H., & Zevenhoven, R. (2020). Towards carbon sequestration using stainless steel slag via phase modification and co-extraction of calcium and magnesium. Process Safety and Environmental Protection, 133, 73–81. https://doi.org/10.1016/j.psep.2019.11.004
109. Zhou, G., Wang, H., Zhang, M., & Guo, M. (2025). Deciphering the reactivity of specific phases in metallurgical slag under direct wet carbonation conditions. Journal of Environmental Chemical Engineering, 13(3), Article 116307. https://doi.org/10.1016/j.jece.2025.116307
110. Zhou, Y., Xia, W., Chen, Y., Wei, G., & Wang, H. (2026). Electric field as a dual-function tool: An electrochemical process intensification strategy for sulfur migration and ladle furnace slag valorization. Chemical Engineering Journal, 535, Article 175702. https://doi.org/10.1016/j.cej.2026.175702
111. Zietsman, J. H., & Pistorius, P. C. (2004). Process mechanisms in ilmenite smelting. Journal of the South African Institute of Mining and Metallurgy, 104(11), 653–660. https://doi.org/10.10520/AJA0038223X_2980.

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