From Ti-Bearing Feed to Aluminous Slag: A Critical Review of Sequential Recovery and Valorization Pathways in Aluminothermic Titanium Processing

Antonio Clareti Pereira, PhD

PhD in Chemical Engineering, University of São Paulo (USP), Belo Horizonte, Minas Gerais, Brazil

DOI: https://doi.org/10.47772/IJRISS.2026.100800381

Received: 21 August 2026; Accepted: 26 August 2026; Published: 05 September 2026

ABSTRACT

Aluminothermic processing of titanium-bearing resources is usually judged by alloy yield, titanium recovery, and alloy chemistry, while the co-generated aluminous slag is treated as a secondary residue. This critical narrative review reframes that slag as a multi-resource stream whose value depends on phase chemistry, elemental deportment, entrained metal, cooling history, and downstream separability, rather than on bulk Al_2O_3 content alone. The evidence base comprises 99 cited publications, predominantly from 2020 to August 2026. Because the original database exports, duplicate logs, exclusion records, exact query dates, and screening histories were not retained, the work is not presented as a PRISMA systematic review and should not be interpreted as exhaustive; the later verification search of 20 August 2026 is reported separately and does not reconstruct the discovery-stage corpus. Evidence is appraised independently by provenance/transferability (D1, D2, T1, T2, or contextual) and by technology scale. Direct evidence is strongest for aluminothermic production of FeTi or Ti–Al alloys and for refractory or ceramic use of real ferrotitanium slag, whereas hydrometallurgical Ti recovery is supported mainly by phase-matched transfer evidence from other Ti-bearing slags. The proposed sequence is to recover entrained FeTi first, evaluate residual Ti second, assess Al recovery or direct Al-bearing phase use third, and then consider refractory or advanced-ceramic applications before bulk use. A six-gate framework links mineralogy, liberation, product qualification, environmental closure, and industrial feasibility. Two worked applications to published real-material aluminothermic cases show how the gates identify both promising routes and missing evidence; importantly, a technical pass at an individual gate does not establish economic feasibility. Slag engineering should therefore begin during charge design, reduction, alloy–slag separation, and cooling.

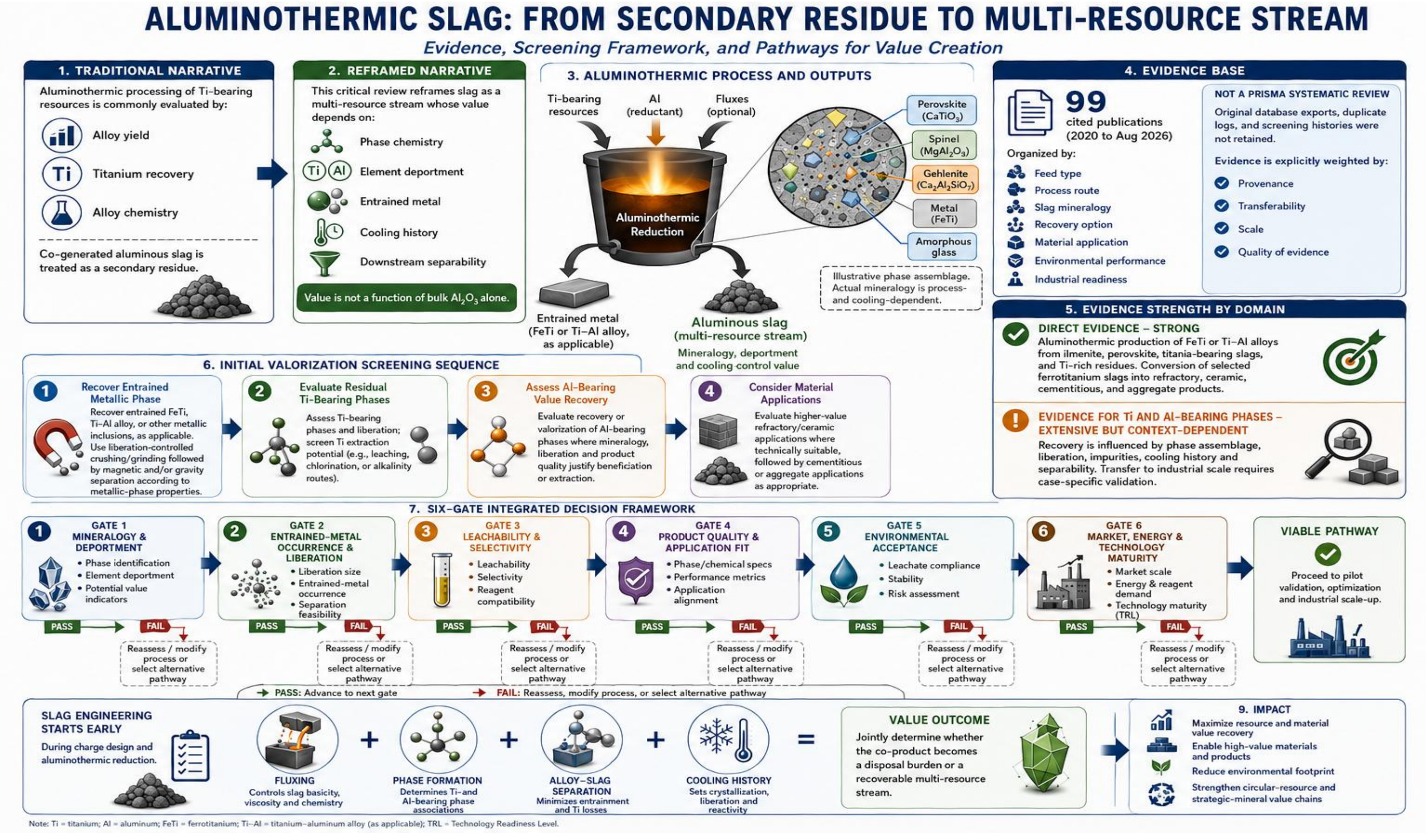
Keywords: Aluminothermic slag; Titanium ores; Ilmenite; Ferrotitanium; Alumina recovery; Slag valorization

Highlights

- Ti aluminothermy generates Al_2O_3-rich slags whose value is controlled by mineralogy, not bulk chemistry alone.
- Entrained FeTi and recoverable Ti should be evaluated before direct use of the bulk slag.
- Calcium aluminates, Al_2TiO_5, spinel, Ti suboxides, and glass control recovery and high-temperature applications.
- A six-gate hierarchy links metal recovery, Al/Ti extraction, materials use, environmental acceptance, and industrial readiness.

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume X Issue VIII August 2026

GRAPHICAL ABSTRACT



INTRODUCTION

Strategic context and the neglected slag question

Titanium extraction and alloy production span mineral beneficiation, smelting, chloride and sulfate routes, and metallothermic reduction. Recent reviews emphasize both the strategic importance of titanium resources and the increasing role of secondary feeds, residues, and recycling in future supply (Feng et al., 2023; Filippou & Hudon, 2020; Matsanga et al., 2025; Song, Dou, Zhang, & Liu, 2021; Takeda et al., 2020; L.-J. Zhang et al., 2026). Within that landscape, aluminothermy occupies a distinctive niche because aluminum is simultaneously a chemical reductant and a major source of the oxide phase that becomes slag. Consequently, the process does not simply divide a Ti-bearing feed into "metal" and "waste"; it creates a coupled alloy–slag system in which the chemistry of one product constrains the chemistry and value of the other. General slag science likewise shows that slag origin, redox history, and phase assemblage are more informative than bulk oxide totals when predicting reactivity or reuse behavior (Matinde & Steenkamp, 2021; Yan et al., 2022).

The literature nevertheless remains strongly alloy-centered. Ilmenite reduction studies are typically framed around FeTi yield, alloy composition, aluminum consumption, reaction kinetics, or sulfur control (C. Cheng et al., 2021; Choi et al., 2020; Gao et al., 2021; Samal et al., 2020). Thermite and metallothermic studies of Ti–Al alloys similarly focus on reduction, metal–slag separation, or alloy refinement (Jiang et al., 2026; Nababan et al., 2026; Song et al., 2023; Song, Dou, Zhang, & Wang, 2021; Z. Tian, Chen, et al., 2025). These objectives are legitimate, but they leave a mass-balance blind spot: aluminous slag can retain titanium as an unreduced oxide or titanate, iron and titanium as entrained alloy droplets, aluminum in several mineral forms, and gangue-derived Ca, Mg, Si, Mn, V, and trace elements. The critical question is therefore not only how much titanium reaches the alloy, but what value remains in the slag and in which phases.

Scope, hypothesis, and objectives

This review focuses on slags generated during, or directly coupled to, aluminothermic processing of Ti-bearing resources. Direct evidence includes ilmenite concentrates, rutile/anatase or TiO_2-based feeds, perovskite/$CaTiO_3$, titania-bearing slags, and Ti-rich industrial residues. Studies of blast-furnace and electric-furnace Ti slags are included only when they provide transferable information on phase equilibria, crystallization, viscosity, selective leaching, environmental behavior, or material applications (Cai et al., 2022; J. Jing et al., 2022; Qu et al., 2024; Shi et al., 2022). This distinction is necessary because a high-Ti blast-furnace slag and an Al_2O_3-rich thermite slag can share phases yet differ strongly in redox state, Ca/Si ratio, metal inclusions, and amorphous content.

The working hypothesis is that valorization cannot be predicted solely from Al_2O_3 content. Recoverability and product quality depend on the joint distribution of Ti and Al among corundum, calcium aluminates, aluminum titanate, spinel, Ti oxides/suboxides, titanates, aluminosilicates, and glass, together with the amount and liberation size of entrained metallic FeTi. The objectives are therefore to: (i) link feed and process conditions to slag formation; (ii) identify mineralogical controls on Ti and Al deportment; (iii) distinguish physical, hydrometallurgical, and materials-based valorization routes; (iv) separate direct evidence from mechanistic analogs; (v) evaluate environmental and economic constraints; and (vi) propose a value-preserving decision framework for industrial route selection.

The coupled material-flow logic developed in this review is summarized in Figure 1, which links Ti-bearing feed selection and charge design to aluminothermic reduction, alloy production, aluminous-slag generation, entrained-metal recovery, and sequential valorization.

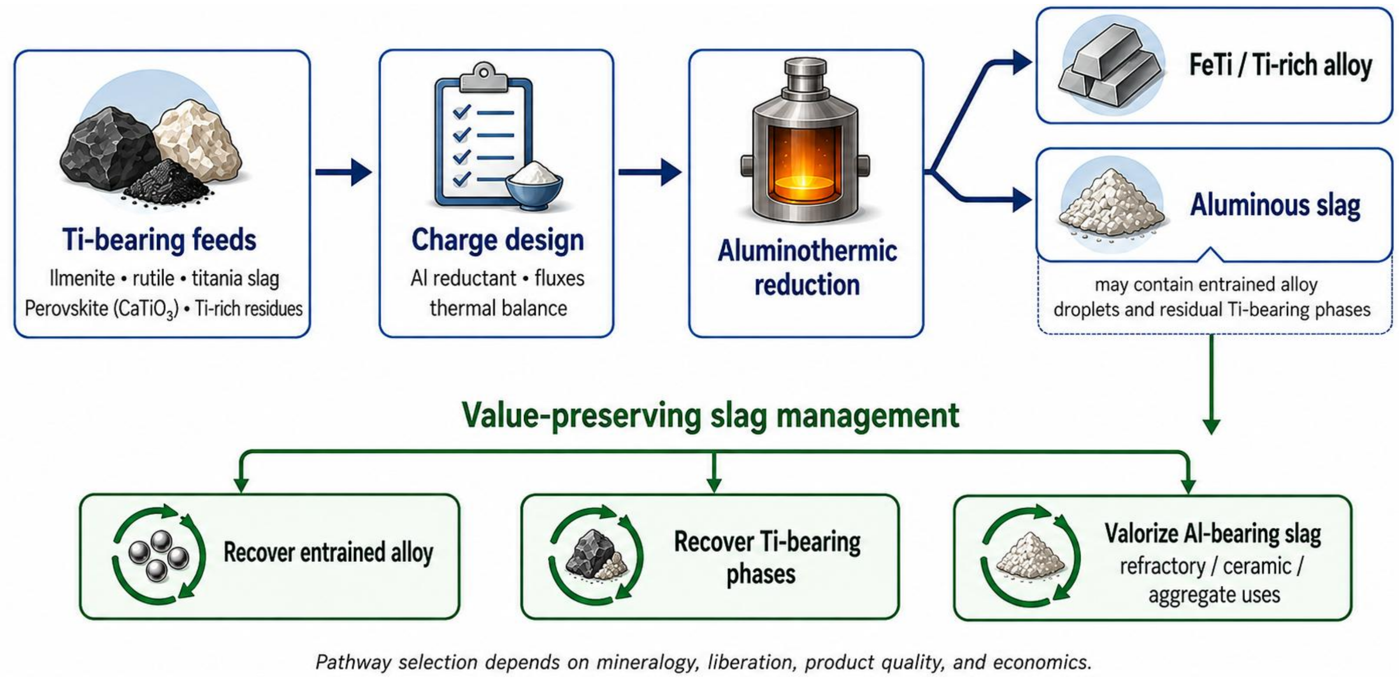


Figure 1. Conceptual material flow from titanium-bearing feed through aluminothermic reduction to alloy, aluminous slag, entrained metal, and sequential valorization pathways.

Note. Author-developed conceptual synthesis based on the cited literature (Choi et al., 2020; Gao et al., 2021; Sparis et al., 2024; J. Yang et al., 2022; You et al., 2024; Q. Zheng et al., 2022; Q. Zheng et al., 2023).

Critical positioning

Figure 1 reframes the aluminothermic circuit as two coupled products rather than a product plus waste. This is consistent with experimental work showing that FeTi can be produced from ilmenite and perovskite while the coexisting slag retains oxide phases that may themselves be engineered or reused (Choi et al., 2020; J. Yang et al., 2022; You et al., 2024; Q. Zheng et al., 2022; Q. Zheng et al., 2023). It is also consistent with the thermodynamic proposal to combine bauxite residue and ilmenite so that alloy production and a potentially cement-compatible slag are considered simultaneously rather than sequentially (Sparis et al., 2024). The implication is important: downstream valorization should influence upstream flux selection, Al dosage, thermal balance, separation time, and cooling practice.

REVIEW METHODOLOGY AND EVIDENCE-APPRAISAL FRAMEWORK

Review design and corpus boundaries

A structured critical narrative approach was adopted because the evidence base spans reaction thermodynamics, metallurgical experiments, phase-equilibrium studies, hydrometallurgy, refractory and ceramic processing, environmental assessment, and techno-economics, with outcomes reported on non-equivalent bases. The current manuscript contains 99 cited publications, predominantly from 2020 to August 2026. The original database export files, duplicate counts, exclusion logs, exact query dates, and record-level screening history were not retained. Consequently, the discovery-stage corpus cannot be independently reconstructed, no PRISMA flow counts or exhaustiveness claim are made, and inter-reviewer agreement cannot be calculated. The later verification search of 20 August 2026 is reported as a distinct activity and is not a surrogate for the unavailable original search history. To strengthen transparency without overstating reproducibility, the revised appraisal separates evidence provenance/transferability from technology scale, reports numerical results only on their original denominators, and provides route-level and claim-level evidence maps in Tables 8–11.

The evidence was organized around seven process-centered domains: titanium extraction and recycling reviews (Feng et al., 2023; C. Li et al., 2025; Qu et al., 2024; Shi et al., 2022; Song, Dou, Zhang, & Liu, 2021; Takeda et al., 2020; Zhang et al., 2026); aluminothermic or thermochemical alloy production (Bhalla & Shukla, 2022; Matsanga et al., 2025; Nababan et al., 2026; Oncel, 2025); Ti-slag physicochemistry and phase equilibria (J. Jing et al., 2022; Yan et al., 2022); physical beneficiation and phase concentration; hydrometallurgical extraction; material applications; and environmental, economic, and scale-up assessment. A final verification search was conducted on 20 August 2026 using Google Scholar query families that combined aluminothermic / thermite / metallothermic with titanium /ferrotitanium/ilmenite/ perovskite and slag/recovery/valorization terms; bibliographic metadata and DOI records were then cross-checked against Crossref and publisher pages. This verification step was used to verify bibliographic metadata and identify potentially relevant late literature for evaluation against the same decision-relevance criterion; it was not used to reconstruct the unavailable original screening counts. A publication was retained when it informed a decision-relevant relationship among feed, process conditions, slag phase assemblage, element deportment, separation, product performance, environmental behavior, or industrial readiness.

Eligibility and two-axis evidence appraisal

Evidence was appraised on two independent axes. The first axis describes provenance and transferability: D1, direct evidence from real aluminothermic slag; D2, direct aluminothermic feed/alloy evidence in which slag behavior is partially characterized; T1, non-aluminothermic Ti-slag evidence with a phase or separation mechanism that can be matched to the target slag; T2, synthetic-slag, equilibrium, modeling, or mechanistic analog evidence; and C, contextual reviews, books, or broader process evidence. The second axis describes technology scale without treating scale as a quality score: industrial/campaign, pilot or semi-pilot, laboratory-real material, synthetic/model, or review/context. A high-maturity transfer study can therefore remain less directly applicable than a laboratory study on real FeTi slag. These descriptors are not validated risk-of-bias grades; they make provenance, scale, and transfer assumptions auditable rather than collapsing them into a single ordinal score. Major synthesis conclusions are additionally summarized in Table 11 with their dominant evidence class, confidence, and the scope of claim considered justified.

To make the review methodology transparent, Table 1 summarizes the review scope, the two-axis evidence-appraisal scheme, the principal data-extraction fields, and the decision rules used to distinguish direct from transferable evidence.

Table 1. Review scope, two-axis evidence appraisal, and critical data-extraction fields.

Element	Review rule	Purpose
Main period	2020–August 2026; 99 cited publications	Capture recent Ti-processing and slag-valorization evidence

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume X Issue VIII August 2026

Element	Review rule	Purpose
Review type	Structured critical narrative review; no PRISMA claim	Match heterogeneous metallurgical, mineralogical, hydrometallurgical, materials, and TEA/LCA evidence
Final verification	20 August 2026; Google Scholar query families + Crossref/publisher DOI checks	Detect late literature and metadata inconsistencies without reconstructing original screening counts
Provenance axis	D1 real aluminothermic slag; D2 aluminothermic feed/alloy; T1 phase-matched Ti-slag transfer; T2 synthetic/model analog; C contextual	Separate directness/transferability from technology maturity
Technology-scale axis	Industrial/campaign; pilot/semi-pilot; laboratory-real material; synthetic/model; review/context	Prevent scale from being conflated with applicability or study quality
Direct evidence	Aluminothermic Ti/FeTi/Ti–Al production; real ferrotitanium slag	Primary basis for process and product conclusions
Transfer evidence	Blast-furnace/electric-furnace Ti slags; synthetic phase systems	Mechanistic support only after phase/redox/separation matching
Extraction fields	Feed, Al/flux basis, temperature, alloy, Ti recovery, slag chemistry/mineralogy, inclusions, cooling, downstream route, environment, scale	Enable phase-resolved comparison
Decision principle	Recover metal → assess Ti → assess Al → high-value material → bulk use → disposal	Preserve optionality and avoid premature downcycling
Quantitative synthesis	No pooled meta-analysis; selected quantitative anchors only when basis is explicit	Avoid false precision across non-equivalent feeds, slags, scales, and product definitions
Search-history boundary	Original exports, duplicate counts, exclusion logs, exact query dates, and screening history unavailable	Retain explicit non-reconstructability limitation

Note. Author-developed evidence-appraisal framework informed by the cited literature (Feng et al., 2023; Jing et al., 2022; Li et al., 2025; Matinde & Steenkamp, 2021; Shi et al., 2022; Takeda et al., 2020; Yan et al., 2022; Zhang et al., 2026).

Critical extraction fields and transfer rules

For each study, the preferred extraction fields were feed mineralogy and Ti grade; aluminum and flux basis; process temperature or thermal mode; alloy composition; Ti recovery where explicitly reported; slag mass, chemistry, and mineralogy; metallic inclusions; residual Ti and Al host phases; cooling history; downstream treatment; environmental test; product specification; and process scale. These fields were selected because nominal bulk composition can conceal structurally important differences in synthetic titania slags (Gupta et al., 2021; Gupta et al., 2022), while hydrometallurgical response depends strongly on mineral phase rather than Ti concentration alone (Schirmer et al., 2020; H. Wang et al., 2023). Missing values were not inferred from unrelated studies, and qualitative comparisons were preferred whenever reported bases were incompatible.

Transfer of evidence follows three rules. First, a route demonstrated on real aluminothermic ferrotitanium slag is treated as directly relevant to the present problem. Second, a route demonstrated on another Ti-bearing slag is treated as transferable only when the controlling phase, redox state, or separation mechanism can plausibly occur in the aluminothermic slag; transfer is therefore phase-conditional rather than composition-only. Third, evidence on bulk utilization is not considered sufficient until higher-value metallic and phase-selective recovery options have been screened. Throughout the review, terms such as direct, transfer, mechanistic, laboratory, pilot, and industrial are used deliberately to preserve this distinction.

Quantitative synthesis and reproducibility boundary

A pooled meta-analysis was not performed because the reviewed studies differ substantially in feed provenance, slag phase assemblage, reaction basis, scale, product target, and response definition. Apparent percentages are therefore not assumed to be directly comparable across studies. Quantitative results are compared only when the denominator and process basis are explicit—for example, recovery relative to contained Ti in the feed, extraction relative to Ti in the treated slag, metal yield relative to charge, or reagent use per unit mass of slag. Table 3 provides selected quantitative anchor points from direct aluminothermic studies without normalizing incompatible bases. Where the reported basis is absent or incompatible, the synthesis emphasizes direction, mechanism, provenance, and scale rather than deriving a normalized value unsupported by the source.

The absence of the original search exports and the record-level screening log still limits the reconstruction of discovery-stage frequencies and precludes the calculation of inter-reviewer agreement. The final verification search does not remove that limitation and cannot convert the review into an exhaustive or reproducible systematic search. No conclusion supported mainly by T1 or T2 evidence is treated as demonstrated on real aluminothermic slag; such evidence is used only for phase-, redox-, or mechanism-conditioned transfer. Consequently, the framework should be read as a transparent critical-synthesis and hypothesis-generating tool rather than a reliability-tested evidence-grading instrument. Each decision gate requires validation on the actual slag, and confidence is derived from the combination of provenance and demonstrated scale rather than citation counts.

Titanium-bearing raw materials and aluminothermic processing routes

Ilmenite, TiO_2-rich concentrates, and reductant demand

Ilmenite is the clearest direct feed for this review because Fe and Ti are already co-located in $FeTiO_3$, allowing aluminothermy to produce an FeTi-rich alloy and an Al-bearing slag in a single operation. Choi et al. investigated FeTi production directly from ilmenite concentrate, while heating-assisted and plasma-based routes sought to improve valuable-element recovery or reduce aluminum demand (Choi et al., 2020; Gao et al., 2021; Samal et al., 2020). The feed gangue remains decisive: MgO, MnO, SiO_2, Al_2O_3, and Cr-bearing components can alter slag liquidus behavior and phase selection, whereas the Fe oxidation state affects both Al consumption and exothermicity. Recycled aluminum can also serve as a reductant, linking the route to secondary-aluminum circularity rather than primary Al consumption alone (Janakiram et al., 2020). However, the use of secondary aluminum introduces an additional feed-quality dimension because scrap origin, chemical composition, oxide and coating load, entrained contaminants, particle size, and batch-to-batch variability can influence charge behavior and impurity input. Although these constraints have been examined primarily in the context of scrap selection and charge design for foundry alloys, they provide a relevant framework for screening secondary aluminum sources intended for metallothermic applications (Pereira, 2026b).

At higher TiO_2 grades, such as rutile/anatase-rich feeds or synthetic TiO_2, the balance shifts toward a larger reductant requirement per unit iron and a stronger tendency to form Ti–Al or Ti-suboxide products if reduction is incomplete or deliberately limited. Experimental work on anatase/rutile reduction and combustion-aluminothermic production of low-oxygen Ti suboxides illustrates that the Ti–O–Al system can be steered toward products other than FeTi (Gulyaeva et al., 2023; Lee et al., 2021). This is relevant to slag valorization because partial reduction may generate useful Ti_2O_3–Al_2O_3 assemblages rather than an inert residual Ti impurity.

Titania slags and smelting-derived intermediates

Titania slag is an intermediate rather than a natural ore, but it is important because it provides a concentrated Ti feed with a mineralogy inherited from smelting. Synthetic slag studies demonstrate how industrially relevant titania slags can be reproduced for controlled phase investigations (Gupta et al., 2021; Gupta et al., 2022), while reviews and smelting studies emphasize the diversity of Ti-bearing electric-furnace slags and their phase

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume X Issue VIII August 2026

transformations (J. Jing et al., 2022; Liao & Zhao, 2022). In aluminothermic use, the value proposition is attractive: an already upgraded Ti-bearing phase can be converted to alloy while producing a second, Al-rich slag. The risk is equally clear: complex initial phases may survive, transform into refractory titanates, or trap metal droplets if the resulting slag is viscous.

Non-aluminothermic smelting literature is therefore most useful here as mechanistic support. Fluxing can alter pseudobrookite formation and Ti distribution (Kim et al., 2020; Myrzakulov et al., 2024), while the phase equilibria of titanomagnetite and ilmenite slags provide boundary conditions for interpreting residual Ti-bearing phases (Liao & Zhao, 2022). Broader literature on iron sand smelting and utilization also reinforces the compositional and process diversity of titaniferous intermediates (Z. Wang et al., 2025). Such studies should inform, but not substitute for, direct characterization of the aluminothermic slag.

Perovskite, vanadium–titanium materials, and secondary residues

Perovskite is particularly important because $CaTiO_3$ introduces calcium directly into the reduction system. Reaction-mechanism studies and subsequent alloy-preparation studies show that ferrotitanium can be produced by aluminothermic reduction of $CaTiO_3$ (perovskite) (J. Yang et al., 2022; You et al., 2024). Compared with rutile-rich feed, this route naturally promotes Ca–Al–Ti–O slag chemistry, thereby increasing the likelihood of calcium aluminates, residual $CaTiO_3$, and complex titanates. Viscosity during separation of metalized perovskite–ilmenite mixtures further confirms that fluidity is a process variable rather than a background property (Vusikhis et al., 2024).

Vanadium–titanium magnetite and related slags expand the feed envelope toward integrated recovery. Fusion/separation and integrated valorization studies demonstrate that Ti can be concentrated in slag while iron or vanadium is recovered in another phase (Z. Guo et al., 2026; S. Yang et al., 2022). More recently, controllable aluminothermic reduction has been applied to vanadium-extraction tailings, reinforcing the broader idea that metallothermy can be used as a selective partitioning tool for secondary resources (Wu et al., 2026). Secondary Ti-bearing residues also include acidic TiO_2 sludge and spent SCR catalysts, from which Ti-rich or Ti-based alloys have been prepared (Thikkandy Edathil et al., 2024; Z. Tian, Zheng, et al., 2025). A multi-residue route using spent SCR catalyst, Ti-bearing blast-furnace slag, and aluminum-alloy scrap demonstrates how reductant, Ti source, and secondary feed can be combined in one materials-circularity concept (Y. Zhang et al., 2022). Such integrated routes also make reductant quality a design variable rather than merely a cost variable, because the composition, provenance, physical condition, and contaminant inventory of aluminum scrap can affect charge predictability and the elements introduced into the metallurgical system (Pereira, 2026b).

The strongest design-oriented example is the bauxite-residue/ilmenite concept, where thermodynamic calculations and batch experiments were used to target FeTi production while also considering further use of the generated slag in cement (Sparis et al., 2024). This is precisely the upstream–downstream integration advocated in the present review.

The principal titanium-bearing feedstocks considered in this review and their expected consequences for aluminothermic slag chemistry, phase development, and evidence transferability are compared in Table 2.

Table 2. Titanium-bearing feedstocks and expected implications for aluminothermic slag.

Feedstock	Dominant Ti form / co-components	Likely slag implication	Evidence role
Ilmenite concentrate	$FeTiO_3$; Mg, Mn, Si, Al, Cr gangue	Al_2O_3-rich slag with Fe/Ti residuals; flux-sensitive separation	Direct
Rutile/anatase/TiO_2	TiO_2-rich, low Fe	Higher Al demand; Ti suboxides/Al–Ti oxide products possible	Direct/mechanistic

Feedstock	Dominant Ti form / co-components	Likely slag implication	Evidence role
Titania slag	Complex Ti oxides from prior smelting	Inherited complex phases; viscosity and crystallization critical	Direct + transfer
Perovskite/$CaTiO_3$	$CaTiO_3$, often with ilmenite	Ca–Al–Ti–O slag; calcium aluminates/titanates likely	Direct
Bauxite residue + ilmenite	Fe–Al–Ti oxides plus Ca/Si/Na depending on residue	Potential co-design of FeTi and cement-compatible slag	Direct thermodynamic/batch
Spent catalyst / Ti-rich residues	Ti with Si, V, W/Mo or process-specific impurities	Broader impurity inventory; alloy or specialty-product opportunity	Direct/secondary-resource

Note. Author-developed synthesis based on the cited literature (Choi et al., 2020; Filippou & Hudon, 2020; Gulyaeva et al., 2023; Gupta et al., 2021; Gupta et al., 2022; Janakiram et al., 2020; Samal et al., 2020; Sparis et al., 2024; Thikkandy Edathil et al., 2024; Z. Tian, Zheng, et al., 2025; Wu et al., 2026; J. Yang et al., 2022; S. Yang et al., 2022; You et al., 2024; Y. Zhang et al., 2022).

Because direct aluminothermic studies report outcomes on different experimental and computational bases, Table 3 compiles selected quantitative anchor points while preserving each source's denominator and reporting basis rather than imposing artificial normalization.

Table 3. Quantitative anchor points from selected direct aluminothermic studies.

Study	Feed/route	Key quantitative conditions	Reported outcome	Evidence
Choi et al. (2020)	Ilmenite concentrate; self-heating aluminothermy	$NaClO_3$ = 20 wt% of TiO_2; recycled Al = 23.8–24.8 wt% of charge; CaO = 16.6 wt% of ilmenite charge	FeTi: 30.2–30.8 wt% Ti; Ti recovery 60.6–68.9%	D2; laboratory-real feed
Samal et al. (2020)	Ilmenite; 30 kW DC plasma carboaluminothermy	CaO/Al_2O_3 = 0.8–1.6; stage-wise reductant addition; 25% excess stoichiometric Al in the reported FeTi26 condition	FeTi26 obtained; calcium titanate/aluminate slag chemistry controlled reduction	D2; laboratory/pilot-like reactor
Gao et al. (2021).	Ilmenite; heating-assisted aluminothermy	Optimal CaO/Al_2O_3 molar ratio = 1:4 for FeTi50 preparation	Improved alloy–slag separation and Fe/Ti recovery relative to no-CaO condition	D2; laboratory-real feed
You et al. (2024)	Perovskite ($CaTiO_3$); aluminothermic FeTi	Reduction temperature 1500→1600 °C; Al addition = 90 mass% of stoichiometric value for qualified alloy	At 1600 °C, alloy–slag separation was effective and Ti recovery exceeded 80%; FeTi50-A obtained	D2; laboratory-real feed

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume X Issue VIII August 2026

Study	Feed/route	Key quantitative conditions	Reported outcome	Evidence
Sparis et al. (2024).	Bauxite residue + ilmenite; autothermic aluminothermy	Successful batch reported for a 50:50 bauxite-residue/ilmenite raw mix with Al, CaO and $NaClO_3$	Commercial-grade FeTi produced at laboratory scale while targeting a cement-compatible slag	D2; laboratory-real feed
Q. Zheng et al. (2023)	Ilmenite; controlled partial aluminothermic reduction	Al/ilmenite molar ratio > 1.4 required for slag–metal separation in the reported system	Controllable Ti_2O_3–Al_2O_3 oxide raw material formed together with separable FeTi	D1/D2; laboratory-real feed
Thikkandy Edathil et al. (2024)	Acidic TiO_2 sludge → roast/magnetic separation → aluminothermy	Feed contained ~48 wt% TiO_2, 15 wt% SiO_2, 11 wt% Fe_2O_3, 4.5 wt% SO_3 and 2 wt% Al_2O_3	Titanium-rich alloy produced after pretreatment and aluminothermic smelting	D2; laboratory-real residue
Wu et al. (2026).	Vanadium-extraction tailings; controllable aluminothermy	Al ratio used to switch between selective and deep reduction	Ti-rich slag with 63.27 wt% TiO_2; FeTi40B alloy with 40.9 wt% Ti under deep-reduction route	D1/D2; laboratory-real residue

Note. Values are reported on the original bases used by the cited studies and are not directly comparable across rows. D1 = direct real aluminothermic-slag evidence; D2 = direct aluminothermic feed/alloy evidence with slag relevance.

Implication for slag design

The feed serves as a precursor to alloy and slag, containing elements like Fe, Ti, Ca, V, W, Mo, Si, and other impurities from sources like ilmenite, perovskite, titania slag, bauxite residue, and spent catalysts. A valorization strategy should predict element distribution—whether they enter the alloy, form oxides, or become environmental concerns.

Formation, chemistry, and mineralogy of Ti-aluminothermic slags

Slag-generation mechanisms and redox coupling

The simplest thermite representation—metal oxide plus Al yielding metal plus Al_2O_3—understates the chemical complexity of Ti systems. Titanium can remain as TiO_2, Ti_2O_3 or other suboxides, dissolve in alloy, enter titanates, or participate in mixed Al–Ti oxide phases. Thermodynamic treatments of ferroalloy production and Ti metallothermy emphasize the strong coupling among oxide activities, metal composition, and the extent of reduction (Bhalla & Shukla, 2022; Nababan et al., 2026; Oncel, 2025). Experimental studies of Ti oxide reduction confirm that phase formation depends on the starting polymorph, temperature, and local redox conditions (Gulyaeva et al., 2023).

The main slag-forming transfers can be described as: Al → Al_2O_3 and aluminates; Ca → calcium aluminates and titanates; Mg → spinel or Mg-bearing silicates; Si → SiO_2/aluminosilicates or partially reduced alloy species; Fe → alloy, oxide, or entrained droplets; and Ti → alloy, TiO_x, titanates, or Al_2TiO_5-like phases. These transfers are not independent. For example, increasing a flux that lowers viscosity may simultaneously change Ti activity and stabilize a different solid phase.

$CaO–Al_2O_3–TiO_2$ and $Al_2O_3–TiO_2$ phase fields

The $CaO–Al_2O_3–TiO_2$ system is a core phase domain for Ca-bearing feeds and lime-fluxed thermite charges. Direct phase-equilibrium work at controlled oxygen partial pressure provides a basis for locating calcium aluminates and Ti-bearing phases within this ternary space (W. Li et al., 2024). In practice, CA ($CaAl_2O_4$), CA_2 ($CaAl_4O_7$), $C_{12}A_7$-type phases, $CaTiO_3$, corundum, Ti oxides, and glass may coexist depending on composition and cooling. The significance for valorization is immediate: calcium aluminates may support hydrometallurgical Al recovery or refractory binder applications, whereas stable $CaTiO_3$ can retain Ti and resist a route optimized for Al extraction.

In the $Al_2O_3–TiO_2$ subsystem, aluminum titanate (Al_2TiO_5) deserves special attention. Ferrotitanium slag has been transformed into or used to stabilize aluminum-titanate ceramics, demonstrating that Ti in an oxide slag can become a functional phase rather than a contaminant (J. Li et al., 2022). Dense $Al_2O_3–Ti_2O_3$ slags synthesized during FeTi production further show that a controlled oxide co-product can be intentionally generated during alloy making (Q. Zheng et al., 2022), and subsequent work produced $Ti_2O_3–Al_2O_3$ raw materials with controlled Ti_2O_3 content from ilmenite aluminothermy (Q. Zheng et al., 2023). These studies support a shift from "slag cleanup" to "co-product engineering."

Multicomponent slag structure, viscosity, and crystallization

Industrial slags rarely remain ternary. $CaO–MgO–SiO_2–Al_2O_3–TiO_2–FeO$ systems have been studied for phase equilibria, thermophysical properties, rheology, melting, and crystallization (J. Guo et al., 2024; Y. Guo et al., 2024; J. Jing et al., 2023, 2024; J.-F. Jing et al., 2024; Ma et al., 2021; Shi et al., 2020; Xu & Wang, 2024; Zhu et al., 2026). Many studies focus on blast or electric-furnace slags rather than aluminothermic slags but reveal three controls: TiO_2 alters melt structure and crystallization; CaO/MgO and CaO/SiO_2 ratios affect polymerization and liquidus behavior; crystallization increases viscosity suddenly. In aluminothermic reduction, a slag that is fluid at peak temperature may lose separation capacity as Ti or aluminous crystals nucleate during settling.

Recent work on ultra-high-Ti slags links microstructure and amphoteric Al behavior to viscous flow and crystallization (B. Zhang et al., 2026; R. Zhang et al., 2025). The transferable lesson is not a single viscosity value, but the need to couple metal-droplet coalescence time to the evolving solid fraction. A process that maximizes chemical reduction while allowing early crystallization can still mechanically lose FeTi.

Fluxes, cooling history, and phase engineering

Flux additions must be assessed simultaneously for reaction heat, liquidus temperature, viscosity, refractory compatibility, and downstream product value. MgO/Al_2O_3 and other ratios influence the thermodynamics and rheology of high-Ti slag (Q. Cheng et al., 2023), while laboratory fluxing studies confirm that additives can substantially alter titanium slag formation (Myrzakulov et al., 2024). MgF_2 has also been used in aluminothermic preparation of Ti–Al alloys, illustrating the role of fluoride-bearing additives in reaction and separation behavior (Z. Tian, Chen, et al., 2025). Because fluoride may complicate downstream leaching, emissions, or residue handling, any metallurgical benefit should be evaluated across the full flowsheet.

Cooling history is the final phase-engineering step. Crystallization studies in Ti-bearing multicomponent slags show that basicity and composition can control the onset and identity of Ti-rich precipitates (Lei et al., 2021; S. Zhang et al., 2021; Zhu et al., 2026). Slow cooling may increase crystal size and liberation but can lock Ti into stable phases; rapid cooling can preserve glass or metastable phases that are more chemically reactive. Silica-mediated selective crystallization and enrichment of rutile illustrates how deliberate phase separation can be used to create a beneficiable Ti-rich product (W. Fan et al., 2026). Thus, cooling should be treated as a beneficiation pre-treatment rather than merely heat rejection.

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume X Issue VIII August 2026

The causal relationships among feed mineralogy, process variables, cooling history, slag phase assemblage, recoverability, high-temperature behavior, and environmental performance are synthesized in Figure 2.

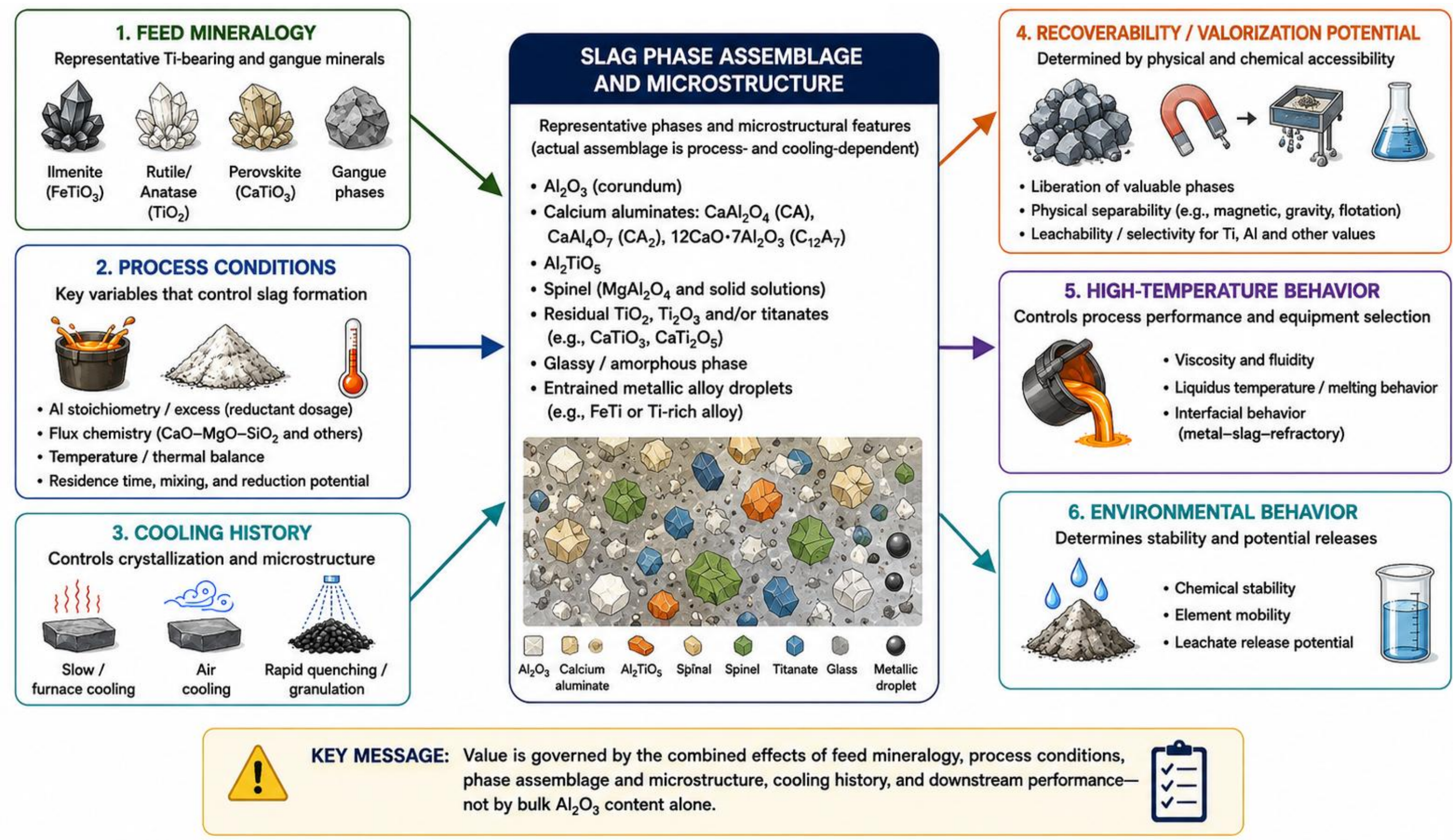


Figure 2. Feed–process–slag phase relationships during aluminothermic processing of titanium-bearing materials.

Note. Author-developed synthesis based on the cited literature (Gulyaeva et al., 2023; J. Guo et al., 2024; Y. Guo et al., 2024; J. Jing et al., 2023; Lei et al., 2021; W. Li et al., 2024; Ma et al., 2021; Shi et al., 2020; Xu & Wang, 2024; B. Zhang et al., 2026; R. Zhang et al., 2025; Zhu et al., 2026).

The principal slag phases discussed above, the conditions that promote their formation, and their implications for downstream valorization are summarized in Table 4.

Table 4. Slag phases, formation controls, and valorization consequences.

Phase/domain	Promoted by	Valorization implication
Corundum (Al_2O_3)	High Al oxidation; low Ca/Mg reaction	Refractory value; difficult hydrometallurgical Al extraction
Calcium aluminates ($CA/CA_2/C_{12}A_7$-type)	Ca-bearing feed or CaO flux	Potential Al extraction; refractory/cement binder routes
Al_2TiO_5	Al–Ti oxide interaction and thermal history	Advanced ceramics; can lock Ti against simple leaching
Ti_2O_3 / Ti suboxides	Partial Ti reduction / controlled redox	Specialty ceramic raw material or Ti-bearing intermediate

Phase/domain	Promoted by	Valorization implication
$CaTiO_3$ / titanates	Ca-rich Ti system	Can retain Ti; selective decomposition may be required
$MgAl_2O_4$ spinel	Mg-bearing feed/flux	Refractory value; chemically resistant Al host
Glass / amorphous Ti-bearing phase	Rapid cooling and suitable composition	Potentially enhanced selective leaching; variable reactivity
Entrained FeTi droplets	High viscosity, poor coalescence, early crystallization	Priority physical recovery before chemical treatment

Note. Author-developed synthesis based on the cited literature (Gulyaeva et al., 2023; J. Guo et al., 2024; Y. Guo et al., 2024; J. Jing et al., 2023; Lei et al., 2021; W. Li et al., 2024; Ma et al., 2021; Shi et al., 2020; H. Wang et al., 2023; B. Zhang et al., 2026; R. Zhang et al., 2025; Q. Zheng et al., 2022; Q. Zheng et al., 2023; Zhu et al., 2026).

Critical synthesis

Figure 2 and Table 4 summarize the controlling logic: feed mineralogy, reductant/flux design, thermal trajectory, and cooling history define the phase assemblage; the phase assemblage then controls liberation, leachability, refractoriness, and environmental behavior. This causal chain explains why two slags with similar Al_2O_3 and TiO_2 assays can have very different value.

Element deportment, metal entrapment, and resource losses

Titanium and aluminum deportment

Titanium deportment should be reported as a phase-resolved balance rather than a single alloy recovery. The metal fraction may contain FeTi or Ti–Al–Fe alloy; the slag can contain residual TiO_2, Ti_2O_3, Al_2TiO_5, $CaTiO_3$, pseudobrookite-type or other complex oxides; and entrained metal droplets can create an apparent “slag Ti” value that is actually physically recoverable alloy. Studies on interface composition and elemental distribution in Ti-bearing slags show that partitioning strongly depends on phase relationships (Han et al., 2025; J.-F. Jing et al., 2026). Direct aluminothermic work on dense Al_2O_3–Ti_2O_3 products confirms that substantial titanium can intentionally remain in the oxide phase (Q. Zheng et al., 2022; Q. Zheng et al., 2023).

Aluminum deportment is equally important. Excess metallic Al can enter the alloy, while oxidized Al can report to corundum, calcium aluminates, spinel, aluminum titanate, aluminosilicates, or glass. These forms have radically different hydrometallurgical behavior. Treating “Al_2O_3 equivalent” as a recoverable alumina inventory therefore overstates value unless quantitative mineralogy is available.

Entrained FeTi and separation losses

Metal–slag separation is not a passive consequence of reduction. Thermite studies of TiAl alloys demonstrate that separation behavior is mechanistically linked to interfacial phenomena, melt fluidity, and coalescence (Pereira, 2026a; Song, Dou, Zhang, & Wang, 2021). In FeTi production, incomplete droplet settling can leave saleable alloy mechanically trapped in the slag even when chemical reduction is satisfactory. The priority consequence is straightforward: crushing and physical recovery of metal may yield higher value at lower chemical intensity than immediate leaching of the entire slag.

The problem is analogous to inclusion and entrainment phenomena in ferroalloys, where non-metallic phases and metallic inclusions affect final alloy quality and yield (Y. Wang et al., 2021). Electromagnetic separation

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume X Issue VIII August 2026

has been used to recover alloy values from Ti-bearing slag systems (Gu et al., 2022), illustrating that enhanced phase separation can be a dedicated recovery operation rather than an incidental step.

Loss mechanisms and required characterization

Five loss mechanisms recur across the evidence: incomplete chemical reduction, premature crystallization, high viscosity, insufficient metal-droplet coalescence, and formation of refractory Ti-bearing phases. These mechanisms cannot be diagnosed by XRF alone. A minimum characterization package for a new aluminothermic slag should combine bulk chemistry, quantitative XRD/Rietveld, polished-section SEM–EDS, automated mineralogy where available, and size-by-size metal accounting. For entrained alloy, image analysis should quantify droplet size and liberation; for chemical recovery, phase-specific Ti-Al associations should be established before selecting reagent chemistry.

This requirement also explains why synthetic or equilibrium studies have limited direct predictive power: they can identify stable phase fields but not the droplet-size distribution, glass fraction, quench history, or microsegregation of an actual thermite slag.

To distinguish chemically bound resource losses from mechanically recoverable losses, Figure 3 maps titanium and aluminum deportment from the reduction zone into saleable alloy, entrained metallic droplets, and the oxide slag matrix.

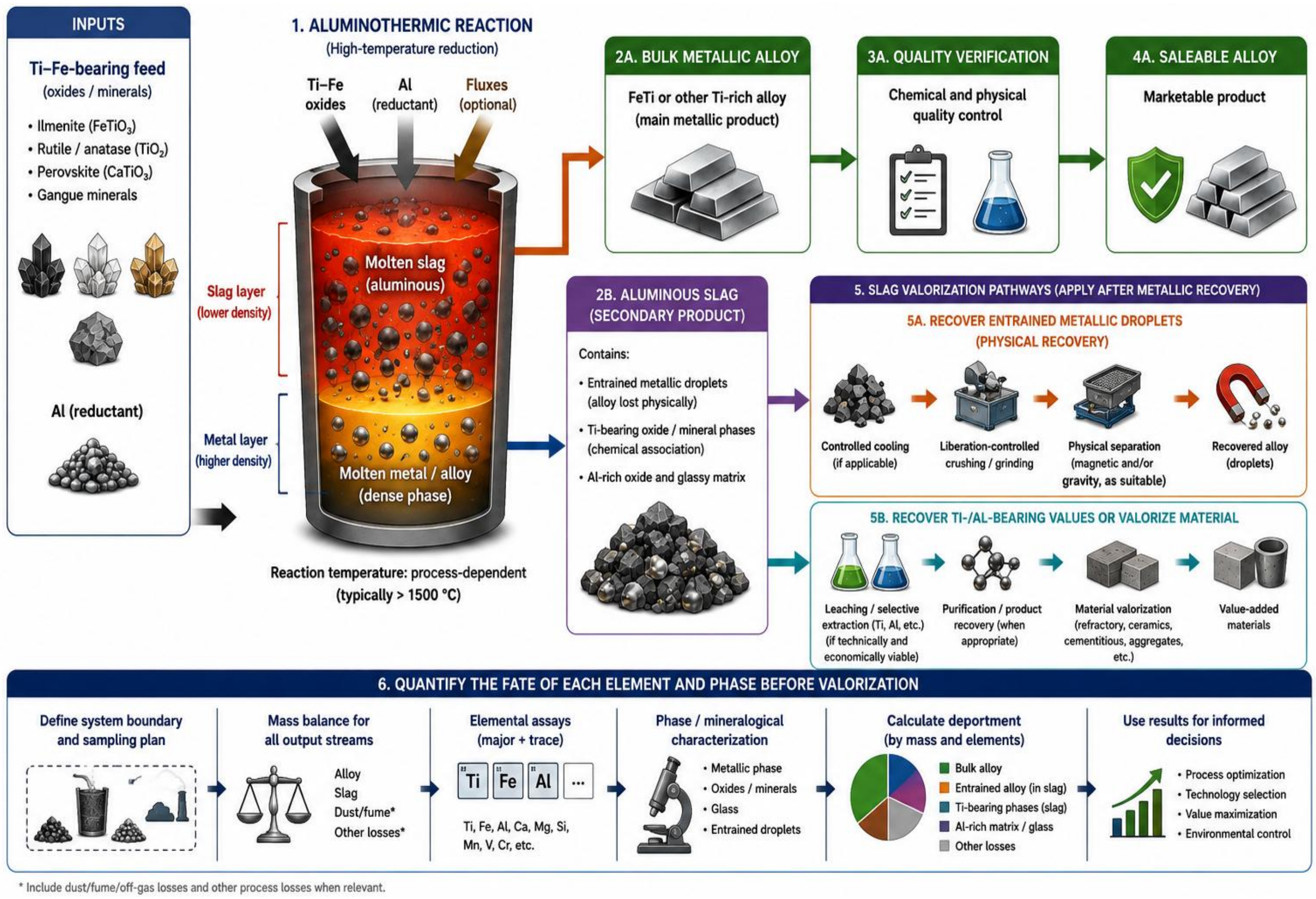


Figure 3. Titanium and aluminum deportment pathways between alloy, entrained metallic droplets, oxide slag, and secondary phases.

Note. Author-developed synthesis based on the cited literature (Han et al., 2025; J.-F. Jing et al., 2026; Song, Dou, Zhang, & Wang, 2021; Y. Wang et al., 2021; Q. Zheng et al., 2022; Q. Zheng et al., 2023).

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume X Issue VIII August 2026

Practical meaning of Figure 3

Figure 3 distinguishes chemically bound Ti/Al from mechanically entrained metal; this distinction underpins the later priority to recover liberatable metallic value before treating the oxide matrix.

Pretreatment and beneficiation of the generated slag

Liberation-centered pretreatment

Pretreatment should begin with a liberation question rather than a standard comminution recipe: what valuable phase must be liberated, at what size, and from which host? Modified upgraded-slag processing demonstrates that controlled beneficiation can convert titaniferous slag into a marketable titania product (Goso et al., 2022), while pre-concentration studies show that titanium can be enriched prior to more reagent-intensive extraction (Y. Li & Yan, 2023). In aluminothermic slag, the immediate physical target is often FeTi or Fe-rich metallic inclusions rather than oxide Ti.

Crushing should therefore be staged and coupled to size-by-size metal recovery. Excessive grinding can generate fines, increase energy consumption, and reduce the selectivity advantage of coarse liberation. If metal droplets are concentrated within a narrow size fraction, classification prior to fine grinding can materially improve process economics.

Magnetic, density, flotation, and advanced separation

Magnetic separation is attractive when FeTi, residual Fe, or magnetic oxide phases are sufficiently responsive. Density-based methods may also be useful because metallic alloy and dense Ti oxides can differ substantially from an aluminous matrix. Electromagnetic separation has demonstrated recovery potential in Ti-bearing slag systems (Gu et al., 2022). Flotation becomes relevant when the target is a specific oxide phase rather than entrained metal: work on Ti_3O_5 and Al_2TiO_5 illustrates that surface properties can be exploited for phase separation, although transfer to a heterogeneous thermite slag requires validation (Ren et al., 2020).

Phase engineering can be combined with beneficiation. High-temperature selective precipitation of perovskite and phase-deconstruction approaches have been used to create separable Ti-rich phases in non-aluminothermic slags (S. Zhang et al., 2021; Y. Zhou et al., 2022). Likewise, silica-mediated phase separation can enrich rutile (W. Fan et al., 2026). These studies suggest an important alternative to “grind finer”: modify the phase assemblage so that the valuable phase becomes coarser or chemically distinctive.

Based on the liberation-centered strategy, Table 5 compares the main physical beneficiation options for Ti-aluminothermic slags in terms of primary target, principal strength, and critical limitation.

Table 5. Physical beneficiation options for Ti-aluminothermic slags.

Operation	Primary target	Strength	Critical limitation
Controlled crushing	Liberate FeTi/metal droplets	Low reagent demand; preserves oxide fraction	Overgrinding can create fines
Size classification	Exploit size-dependent liberation	Reduces mass sent to fine grinding	Requires size-by-size metal accounting
Magnetic separation	FeTi, Fe-rich metal, magnetic oxides	Simple dry/wet operation	Response depends on alloy/oxide mineralogy
Density separation	Metal and dense Ti phases	Potentially high selectivity at coarse size	Fine particles reduce efficiency

Operation	Primary target	Strength	Critical limitation
Flotation	Specific Ti oxide phases	Can target nonmagnetic mineral phases	Surface chemistry must be validated on real slag
Phase engineering + separation	Rutile/perovskite/Ti-rich crystals	Creates a separable target before grinding	Adds thermal processing and complexity

Note. Author-developed synthesis based on the cited literature (W. Fan et al., 2026; Goso et al., 2022; Gu et al., 2022; Y. Li & Yan, 2023; Ren et al., 2020; S. Zhang et al., 2021; Y. Zhou et al., 2022).

Critical energy–value criterion

The beneficiation decision should compare the marginal recovery value against the comminution and separation costs. If a slag contains only a small amount of finely disseminated FeTi, ultra-fine grinding may destroy the economic advantage of physical recovery. Conversely, even modest metal contents can justify coarse crushing if droplets are liberated at millimeter or sub-millimeter scale. This criterion should be reported explicitly in future studies as recovered metal per unit comminution energy, not merely as concentrate grade.

Recovery of residual titanium and metallic values

Physical recovery and reprocessing before leaching

Entrained FeTi should be recovered first whenever liberation is feasible. The recovered metallic concentrate can potentially return to alloy refining, while the cleaned oxide fraction becomes a more homogeneous feed for Ti or Al extraction. Reprocessing of Ti-rich slag fractions can also be considered through pyrometallurgical or hybrid routes. Alloying and separation studies, Ti-rich material preparation, and integrated slag valorization demonstrate that a staged approach can concentrate value before hydrometallurgy (Gu et al., 2022; Z. Guo et al., 2026; Y. Zhou et al., 2022).

Direct aluminothermic routes can also be redesigned to reduce the residual Ti inventory in the first place. Heating-assisted FeTi preparation, thermodynamic optimization, and kinetic studies indicate that reductant efficiency and reaction pathway can be improved upstream (Gao et al., 2021; Oncel, 2025; J. Yang et al., 2022). The critical review perspective is therefore to compare “recover Ti from slag” with “prevent Ti from entering slag,” because the latter may have lower overall energy and reagent demand.

Acid, sulfate, ammonium, and fluoride routes

A large body of hydrometallurgical literature exists on Ti-bearing blast-furnace and electric-furnace slags. Sulfate-based routes include ammonium sulfate pyrolysis/acid leaching, sulfuric acid roasting, two-stage sulfuric acid leaching, and pressure-assisted processes (Bian et al., 2020; Nie et al., 2023; Zai et al., 2025; L. Zhou et al., 2022). Acid leaching has also been used to extract other valuable metals (Liu et al., 2024). These routes demonstrate that Ti can be mobilized or concentrated, but its transfer to aluminothermic slag depends on whether Ti is present in acid-responsive phases rather than refractory Al_2TiO_5, spinel-associated phases, or dense titanates.

Fluoride chemistry provides another pathway. Fluoroammonium processing and $[NH_4^+]$–$[F^-]$ leaching have been used to attack Ti-bearing slags (Dmitriev et al., 2022; F. Zheng et al., 2021), and phase-controlled fluoride leaching has emphasized the importance of reagent ratio and phase selection (J. Zhang et al., 2026). Fluoride routes can be highly selective for Ti, but their industrial attractiveness must be balanced against reagent recovery, corrosion, wastewater chemistry, and fluorine management.

Recent selective leaching of an amorphous Ti phase is particularly relevant to the cooling argument: if rapid or controlled cooling preserves a leachable, amorphous, Ti-bearing fraction, slag solidification can directly improve downstream extraction (S. Cheng et al., 2026). This is a strong example of process integration across the hot and hydrometallurgical stages.

Phase-selective recovery and product form

Mineral phase controls leaching efficiency. Comparative work has shown that Ti-slag leachability changes with mineralogical assemblage (H. Wang et al., 2023), while thermodynamic and experimental studies of waste slags demonstrate the value of predicting which phases can be selectively decomposed (Kumai et al., 2024; Z. Wang et al., 2020). Pressure leaching can also mobilize Ti together with Al and Mg, creating both an opportunity and a separation challenge (Yuan et al., 2024). One-step separation of Mg and Ca from high-Ti slag illustrates another strategy: remove matrix-forming elements to upgrade the Ti-bearing residue rather than dissolve Ti first (Liu et al., 2026).

The target product should be defined before selecting chemistry. For many slags, producing a TiO_2-rich concentrate, metatitanic acid, or another Ti precursor may be more feasible than attempting direct production of titanium metal. Perovskite-type slags have been processed to metatitanic acid (M. Tian et al., 2022), and broader reviews document diverse routes from Ti-bearing secondary resources to concentrates or compounds (C. Li et al., 2025; Qu et al., 2024; Shi et al., 2022; L.-J. Zhang et al., 2026).

After physical recovery of liberatable metal, the principal routes for residual titanium and metallic-value recovery are compared in Table 6 by mechanism or product, best-fit conditions, and main limitations.

Table 6. Titanium and metallic-value recovery routes from Ti-bearing slags.

Route	Mechanism/product	Best-fit condition	Main limitation
Physical FeTi recovery	Liberation + magnetic/density separation	Liberatable entrained alloy	Not effective for chemically bound Ti
Reprocessing/remelting	Return Ti-rich fraction to metallurgical circuit	Concentrated oxide or metal-bearing fraction	Energy and impurity accumulation
Sulfate/acid routes	Dissolution or roasting–leaching to Ti precursor	Acid-responsive Ti phases	Acid use, impurity co-dissolution, residue
Ammonium-salt routes	Phase conversion then aqueous recovery	Slags amenable to salt-assisted decomposition	Salt recycle and off-gas management
Fluoride routes	Complexation / selective Ti dissolution	Refractory Ti phases with favorable selectivity	Fluoride handling, corrosion, wastewater
Matrix removal	Remove Ca/Mg/Si to enrich Ti residue	Ti phase remains stable while gangue dissolves	May transfer Al or generate large liquor volume
Selective crystallization	Create rutile/perovskite/Ti-rich phase	Melt can be thermally reprocessed	Additional heat and phase-control requirement

Note. Author-developed synthesis based on the cited literature (Bian et al., 2020; S. Cheng et al., 2026; Dmitriev et al., 2022; G. Fan et al., 2021; W. Fan et al., 2026; Goso et al., 2022; Kumai et al., 2024; Y. Li & Yan, 2023; Liu et al., 2024; Liu et al., 2026; Nie et al., 2023; M. Tian et al., 2022; H. Wang et al., 2023; Z. Wang et al., 2020; Yuan et al., 2024; Zai et al., 2025; J. Zhang et al., 2026; F. Zheng et al., 2021; L. Zhou et al., 2022; Y. Zhou et al., 2022).

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume X Issue VIII August 2026

Transferability limits

The main limitation in this evidence domain is provenance. Most modern Ti-slag leaching studies were not performed on aluminothermic FeTi slag, so their value lies primarily in phase–reagent relationships rather than in proving equivalent recovery from thermite slag. Transfer is strongest when the aluminothermic material contains the same controlling Ti host phase, comparable redox state, and similar matrix chemistry; it is weak when the target is locked in Al_2TiO_5, spinel-associated domains, dense titanates, or a glass fraction unlike that of the source study. Future work should therefore first characterize real aluminothermic slag, identify the dominant Ti phases and their liberation, and only then select candidate chemistries from the broader Ti-slag literature.

Recovery of aluminum and alumina-bearing products

Why Al_2O_3 content is not a recovery metric

Aluminum is the defining co-product element of aluminothermy, yet it is rarely treated as a recoverable value in FeTi studies. The central error is to equate bulk Al_2O_3 with recoverable alumina. Corundum, calcium aluminates, $MgAl_2O_4$, Al_2TiO_5, Ti_2O_3–Al_2O_3 solid or composite phases, aluminosilicates, and glass have different dissolution and product-forming behavior. Phase-equilibrium work in the CaO–Al_2O_3–TiO_2 system and direct synthesis of Al_2O_3–Ti_2O_3 slag demonstrate why phase identity must precede extraction design (W. Li et al., 2024; Q. Zheng et al., 2022).

If Al is concentrated in calcium aluminates, selective dissolution or conversion to $Al(OH)_3/Al_2O_3$ may be plausible. If it is mainly corundum or spinel, aggressive chemistry or high-temperature pretreatment may be required, potentially eliminating the economic advantage of recovery. If Al occurs with Ti in Al_2TiO_5 or related phases, dissolution may co-extract Ti and create a purification burden.

Hydrometallurgical possibilities and Al–Ti separation

The broader Ti-slag literature demonstrates several matrix-control strategies that are informative for Al recovery. Acid pressure treatment can co-leach Ti, Al, and Mg (Yuan et al., 2024), while selective Mg/Ca removal can simplify the residual Ti–Al matrix (Liu et al., 2026). Generic slag-processing literature also emphasizes selective precipitation as a means of recovering multiple components from a common leachate (Sui et al., 2026). These concepts can be adapted to aluminothermic slags, but only if speciation, silica behavior, and impurity carryover are quantified.

A practical Al flowsheet should therefore be designed backward from product specification. Low-purity aluminum salts may tolerate more co-dissolved Ti/Fe than smelter-grade or high-purity alumina. High-value alumina claims require evidence for impurity removal, precipitation selectivity, calcination, yield, and residue closure. Without those steps, “Al extraction” is not equivalent to an alumina product.

Co-product engineering instead of extraction

An alternative is to use the Al-bearing phase directly. Dense Al_2O_3–Ti_2O_3 slag and controlled Ti_2O_3–Al_2O_3 raw materials show that the oxide product of FeTi production can be intentionally engineered as a ceramic feed rather than dissolved and re-precipitated (Q. Zheng et al., 2022; Q. Zheng et al., 2023). This route can avoid reagent consumption and secondary aqueous residues, but it requires reproducible composition and control of metallic inclusions. The economic choice between extraction and direct material use therefore depends on phase purity, market specification, and the scale of the slag stream.

The sequential integration of entrained-FeTi recovery, residual-titanium recovery, aluminum recovery, and residue closure is illustrated in Figure 4, emphasizing that each step should preserve the value and processing optionality of the remaining stream.

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume X Issue VIII August 2026

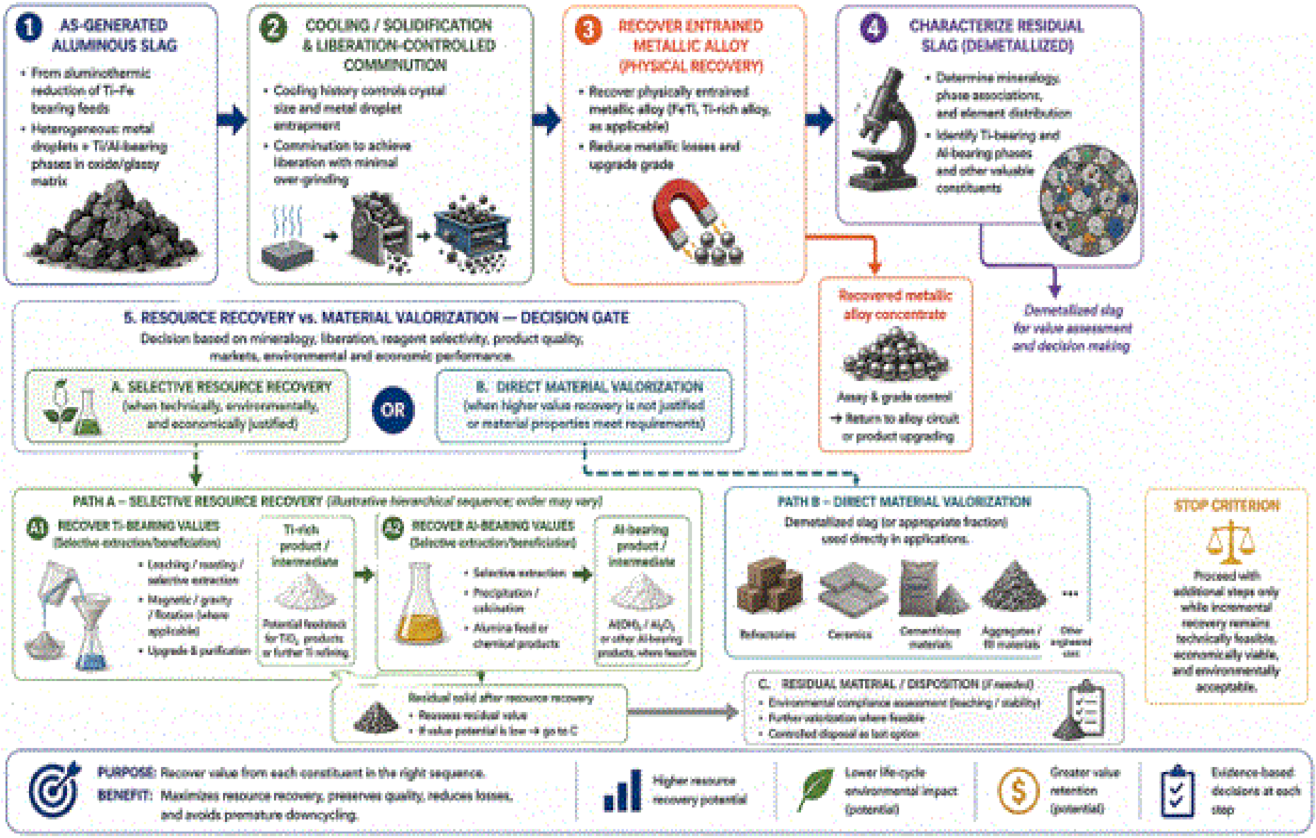


Figure 4. Integrated recovery concept for entrained FeTi, residual titanium, and aluminum value from Ti-aluminothermic slag.

Note. Author-developed synthesis based on the cited literature (Goso et al., 2022; Gu et al., 2022; Y. Li & Yan, 2023; Liu et al., 2026; Schirmer et al., 2020; H. Wang et al., 2023; Yuan et al., 2024).

Residue closure

Figure 4 also makes residue closure explicit: sequential recovery is circular only when the remaining Ca–Si–Fe–Mg–Ti solids and process liquors are mass-balanced, environmentally qualified, and assigned a defensible destination.

Refractory and advanced ceramic applications

Direct evidence for ferrotitanium-slag ceramics

Refractory and ceramic use is the strongest direct materials-valorization domain in the supplied corpus. Ferrotitanium slag has been evaluated for potential use as a refractory raw material through remelting, with attention to its thermal characteristics and stability (Y. Li, Zhao, et al., 2022). It has also been incorporated into Al_2O_3–SiC–C castables based on structural commonalities between Ti–alumina slag and calcium alumino-titanate phases (Y. Li, Zhang, et al., 2022). These studies move beyond generic “slag in ceramics” claims because the actual FeTi slag is the feedstock.

Aluminum titanate is particularly compelling. Ferrotitanium slag has been used to improve phase stability and mechanical properties of Al_2TiO_5-based ceramics (J. Li et al., 2022), and Al_2O_3–TiO_2–CaO composite materials have been prepared from ferrotitanium slag (F. Zhang et al., 2023). The material logic is strong: the slag already contains the Al–Ti–Ca chemistry required for high-temperature phases, potentially reducing virgin raw material demand.

Performance opportunities and constraints

Potential products include alumina-rich refractory aggregate, Al_2O_3–TiO_2 refractories, aluminum-titanate ceramics, spinel-containing products, calcium-aluminate binders, ceramic aggregates, and glass-ceramics.

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume X Issue VIII August 2026

However, suitability depends on much more than refractory oxide content. Residual Fe can lower refractoriness or create redox-sensitive phases; glass can improve sintering but reduce high-temperature stability; entrained metal can oxidize during firing; and thermal expansion mismatch can cause cracking. Aluminum titanate itself is attractive for thermal-shock resistance but requires control of decomposition and mechanical strength.

Refractory compatibility must also be assessed during the aluminothermic process itself. Corrosion studies of carbon, Al_2O_3, and MgO refractories during Ti–Si–Al alloy production demonstrate that the slag can aggressively interact with lining materials (Y. Zhang et al., 2021). This affects both process reliability and contamination of the slag co-product.

For the material-use branch of the valorization hierarchy, Table 7 summarizes the principal refractory and advanced-ceramic applications, the slag attributes required for each route, the potential benefit, and the critical qualification check.

Table 7. Refractory and ceramic applications of ferrotitanium and Al–Ti slags.

Application	Required slag attribute	Potential benefit	Critical check
Alumina-rich refractory feed	High Al_2O_3, low deleterious glass/metal	Substitutes part of bauxite/alumina	Refractoriness, variability, Fe content
Al_2O_3–SiC–C castable component	Compatible Ti–Al–Ca phase chemistry	Functional aggregate/filler contribution	Oxidation and hot-strength behavior
Aluminum-titanate ceramic	Suitable Al–Ti oxide inventory	Thermal-shock-resistant phase system	Phase decomposition and mechanical strength
Al_2O_3–TiO_2–CaO composite	Controlled Ca–Al–Ti phase evolution	Uses slag chemistry directly	Sintering window and impurity control
Spinel-bearing refractory	$MgAl_2O_4$ or Mg-rich precursor	High-temperature stability	Mg/Al distribution and unwanted low-melting phases
Calcium-aluminate binder	CA/CA_2-rich phase assemblage	Higher-value binder route	Hydration/mineralogy reproducibility

Note. Author-developed synthesis based on the cited literature (J. Li et al., 2022; Y. Li, Zhang, et al., 2022; Y. Li, Zhao, et al., 2022; F. Zhang et al., 2023; Y. Zhang et al., 2021; Q. Zheng et al., 2022; Q. Zheng et al., 2023).

Critical market criterion

High-temperature applications preserve more value than aggregate use but have smaller markets and tighter specifications. A slag-derived refractory feed must therefore be reproducible across batches, not merely successful in a single laboratory formulation. The key scale-up questions are composition variability, metal removal, particle-size control, firing behavior, impurity accumulation, and the substitution level at which performance remains competitive with bauxite, calcined alumina, tabular alumina, chamotte, or synthetic spinel.

Cementitious and construction-material applications

Cement is not the default destination

Bulk construction applications can consume large volumes of slag, but they should be positioned late in the value hierarchy. Reviews of Ti-bearing slag utilization often include cementitious routes because large tonnage and aluminosilicate chemistry make them operationally attractive (Cai et al., 2022; Jing et al., 2022; Zhang et al., 2026). Yet an aluminothermic slag containing recoverable FeTi, Ti-rich phases, or useful calcium aluminates may be economically downcycled if it is immediately ground into clinker raw meal or aggregate.

The most defensible cement route is one designed from the beginning. Thermodynamic work on bauxite residue plus ilmenite explicitly considered production of an FeTi alloy in parallel with a slag suitable for further cement valorization (Sparis et al., 2024). In that case, cement compatibility becomes a co-product design target rather than an after-the-fact disposal option.

Portland clinker, calcium-aluminate cement, and SCM behavior

For Portland clinker raw materials, the relevant questions are the contributions of Ca, Al, Si, and Fe; the effects of Ti on clinker mineralogy; the alkali and trace-element load; and burnability. For calcium-aluminate cement or refractory binder, a slag rich in CA/CA_2-like phases may be more chemically aligned than Portland cement. For supplementary cementitious use, high Al_2O_3 alone is not evidence of reactivity: glass content, depolymerization, Ca availability, fineness, and dissolution kinetics must be established.

Life-cycle work comparing titanium slag and granulated blast-furnace slag as cementitious materials demonstrates that environmental performance depends on both material activity and the avoided burdens assigned to the substitute (Tao et al., 2022). This is an important methodological warning: a low-activity slag may require more grinding, activator, or clinker, reducing the apparent benefit.

Aggregates and geotechnical use

Aggregate or road-base use has the lowest processing barrier but also the highest risk of value destruction. Such use is appropriate only after the recoverable alloy and the Ti/Al value have been rejected on technical or economic grounds, and after volume stability and leaching acceptance have been demonstrated. The hierarchy is therefore not anti-cement or anti-aggregate; it is a safeguard against prematurely converting a potentially strategic-resource stream into a low-value bulk material.

Other high-value and emerging applications

Alloy and specialty-oxide routes

Some Ti-bearing residues are better viewed as feedstocks for specialty alloys or functional oxides than as sources of isolated Ti or Al. Ti-bearing slags and residues have been converted by aluminothermic routes to Ti–Al, Ti–Si–Al, and related alloys (Piao et al., 2020; Ding, 2024; Song et al., 2023; Zhang et al., 2022), while controlled reduction can intentionally generate low-oxygen Ti suboxides or Ti_2O_3–Al_2O_3 co-products (Lee et al., 2021; Zheng et al., 2022; Zheng et al., 2023). The relevant question is therefore whether residual Ti is a loss or a specification-compatible functional phase.

Photocatalytic, adsorptive, pigment, and composite concepts

Potential emerging applications include pigments, photocatalytic materials, adsorbents, catalyst supports, wear-resistant ceramics, and specialty composites, but direct aluminothermic-slag evidence is much weaker than for refractory ceramics. These concepts should therefore remain research opportunities until phase purity, Fe content, surface area, trace-element host phases, product performance, and the consequences of fine grinding are demonstrated; the thorium-speciation work on titania slag illustrates why a material acceptable as a dense product may not remain acceptable after surface-area-intensive processing (Chadirji-Martinez et al., 2025).

Market-size discipline

High unit value does not guarantee whole-stream impact: specialty products may absorb only a small fraction of slag, whereas lower-value construction routes can provide volume closure. A practical cascade may therefore

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume X Issue VIII August 2026

recover a small high-value metal/mineral fraction first and direct the environmentally acceptable remainder to larger markets.

Environmental performance, techno-economics, circularity, and decision framework

Environmental characterization and leaching

Environmental acceptance must be assessed at four states: as-generated slag, beneficiated slag, process residue, and final product. This distinction matters because crushing increases surface area, leaching changes mineral hosts, and thermal treatment can either immobilize or mobilize trace elements. Thorium speciation work in titania slag illustrates the value of identifying host phases rather than relying on bulk concentration alone (Chadirji-Martinez et al., 2025). More broadly, reviews of titanium-bearing secondary resources stress the need to integrate environmental behavior with resource recovery (Feng et al., 2023; L.-J. Zhang et al., 2026).

Potentially relevant elements depend on the feed and include Cr, V, Mn, Ni, Pb, As, Th, and other trace constituents. A slag produced from clean ilmenite and aluminum is fundamentally different from one generated from spent catalysts, bauxite residue, or vanadium-bearing tailings. Environmental testing must therefore align with the actual feed blend and the intended use of the product.

Environmental screening should be phase-resolved rather than based only on total concentration. Cr and V may be retained in oxide or spinel-like hosts, whereas As, Pb, Ni, Mn, Th, and fluorine-bearing species can become more mobile after grinding, oxidation, or chemical treatment. The minimum route-specific program should therefore pair total chemistry with host-phase identification and leaching tests appropriate to the intended use; fluoride-bearing hydrometallurgy additionally requires a fluorine mass balance, reagent-recycle assessment, corrosion control, and characterization of the final aqueous and solid residues. Acceptance criteria must be applied to the marketed product and every intermediate residue, not inferred from the as-generated slag.

Mass and energy balance as minimum evidence

A credible valorization study should close Ti, Al, Fe, Ca, and, preferably, Mg/Si mass balances across the alloy, slag, entrained metal, leachate, precipitate, and residue. Yield claims without slag mass and composition cannot establish resource efficiency. This is especially important for integrated concepts such as bauxite residue/ilmenite aluminothermy, where the objective is the simultaneous recovery and slag design (Sparis et al., 2024). Energy accounting should include feed preparation, Al reductant production or recycling credit, reaction preheating, remelting, cooling/granulation, comminution, leaching, reagent regeneration, and product calcination.

The economic comparison must include the counterfactual. A route that appears expensive relative to zero-cost slag may be favorable relative to landfilling plus the loss of FeTi value; conversely, a hydrometallurgical route may be unattractive if physical metal recovery and direct refractory use capture most of the available value.

Techno-economics, LCA, and industrial readiness

Techno-economic evidence remains sparse for the specific aluminothermic-slag problem. Discounted cash flow analysis has been applied to vanadium extraction from titaniferous slag (Nkosi et al., 2026), providing a useful template for moving beyond laboratory recovery percentages. Life-cycle assessment has been applied to Ti slag in cementitious use (Tao et al., 2022). These studies show the types of metrics required—capital intensity, reagent and energy consumption, avoided disposal, product credit, and sensitivity to market price—but they do not substitute for route-specific evaluation of FeTi slag.

In aluminothermy, the source of the aluminum reductant can dominate the overall flowsheet environmental burden. Route-specific LCA should therefore distinguish primary from recycled Al and include scrap sorting/preparation, oxide or dross losses, electricity and thermal inputs, and any allocation of burdens between alloy and slag co-products. Credits for recovered FeTi, for avoiding virgin Ti or alumina feed, and for avoiding disposal should be reported transparently, while acid or fluoride routes should include reagent regeneration and

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume X Issue VIII August 2026

wastewater treatment. A slag-valorization route should not be labeled circular solely because it diverts material from landfill.

Industrial readiness should be stated separately from technical feasibility. Direct aluminothermic studies are mostly laboratory or batch demonstrations, and many hydrometallurgical and ceramic routes remain at laboratory scale. A technically feasible route demonstrates the intended separation, conversion, or product performance under defined conditions; economic feasibility additionally requires route-specific mass and energy closure, capital and operating costs, reagent recycle, residue liability, market capacity, logistics, product credit, and sensitivity analysis. The available reviews and integrated-use studies therefore support screening of plausible flowsheets rather than assuming commercial viability (C. Li et al., 2025; Takeda et al., 2020; L.-J. Zhang et al., 2026). Routes that combine multiple unproven unit operations should be assigned lower industrial confidence even when laboratory extraction is high.

Value-preserving hierarchy

The proposed hierarchy is a default screening sequence rather than a universal economic ranking. Its organizing principle is reversibility: once a slag is diluted into concrete or aggregate, recovery of FeTi, Ti, or Al becomes effectively impractical, whereas physical metal recovery leaves the oxide fraction available for subsequent extraction or material use. Ti recovery can often preserve part of the Al value, and Al recovery may leave a Ca–Si-rich residue suitable for lower-value use. However, site-specific market capacity, logistics, energy and reagent prices, product specifications, environmental obligations, and capital intensity can reorder the preferred route. Accordingly, the hierarchy should be applied alongside route-specific techno-economic and life-cycle assessments rather than as a fixed prescription.

The practical objective is therefore to preserve optionality until higher-value fractions have been assessed, while allowing a lower-value bulk route to become preferred when it provides the best combination of market absorption, environmental acceptance, and whole-flowsheet economics.

The value-preserving sequence derived from the evidence synthesis is presented in Figure 5, prioritizing reversible recovery steps before lower-value bulk utilization or final-residue management.

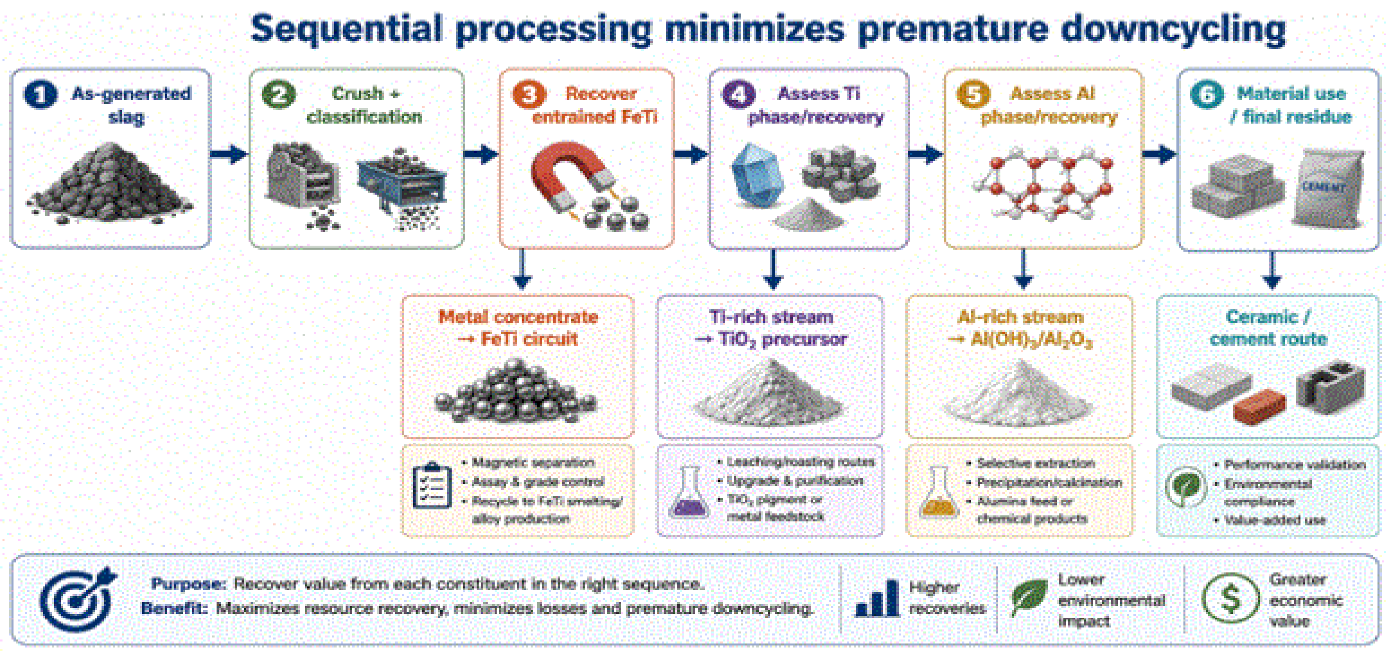


Figure 5. Sequential value-preserving hierarchy for Ti-aluminothermic slag, from entrained alloy recovery to material use and final residue.

Note. Author-developed framework based on the evidence synthesized in Sections 5–12 and the cited literature (C. Li et al., 2025; Sparis et al., 2024; Takeda et al., 2020; L.-J. Zhang et al., 2026).

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume X Issue VIII August 2026

Six-gate decision framework

Figure 5 ranks routes by preservation of recoverable optionality, while Figure 6 converts that logic into a six-gate screening sequence. The gates are conditional rather than prescriptive. Gate 1 asks whether entrained metallic FeTi is present at a grade and liberation size that justify physical recovery. Gate 2 asks whether residual Ti occurs in a phase that can be beneficiated, selectively decomposed, or converted to a defined Ti product. Gate 3 asks whether Al is hosted in a selectively recoverable phase or in an Al-bearing phase that has direct material value. Gate 4 tests whether the cleaned slag or the selected fraction meets specifications for refractory, ceramic, or other higher-value products. Gate 5 considers cementitious, aggregate, or geotechnical use only after the higher-value options have been screened. Gate 6 requires environmental closure and industrial feasibility for the selected route, including the final product and any intermediate residue.

For decision transparency, the qualitative descriptors in Table 8 are assigned by explicit rules. Relative value preservation reflects how much metallic or strategic-element optionality remains after a route is selected; process intensity reflects the number and severity of thermal and chemical operations; residue risk reflects the amount and complexity of secondary streams and uncertainty in leaching behavior; and market/maturity reflects market capacity together with the largest demonstrated scale of the relevant unit operations. Evidence confidence is high when direct real-slag evidence is supported by pilot/industrial demonstration or several consistent real-material studies, moderate when it rests on direct laboratory evidence or closely phase-matched transfer evidence, and low when it depends mainly on synthetic/modeling/contextual evidence. These categories are screening descriptors, not numerical TEA or LCA outputs.

To convert the proposed hierarchy into an operational screening tool, Figure 6 presents the six-gate framework linking mineralogy, liberation, recoverability, product qualification, environmental closure, and industrial feasibility.

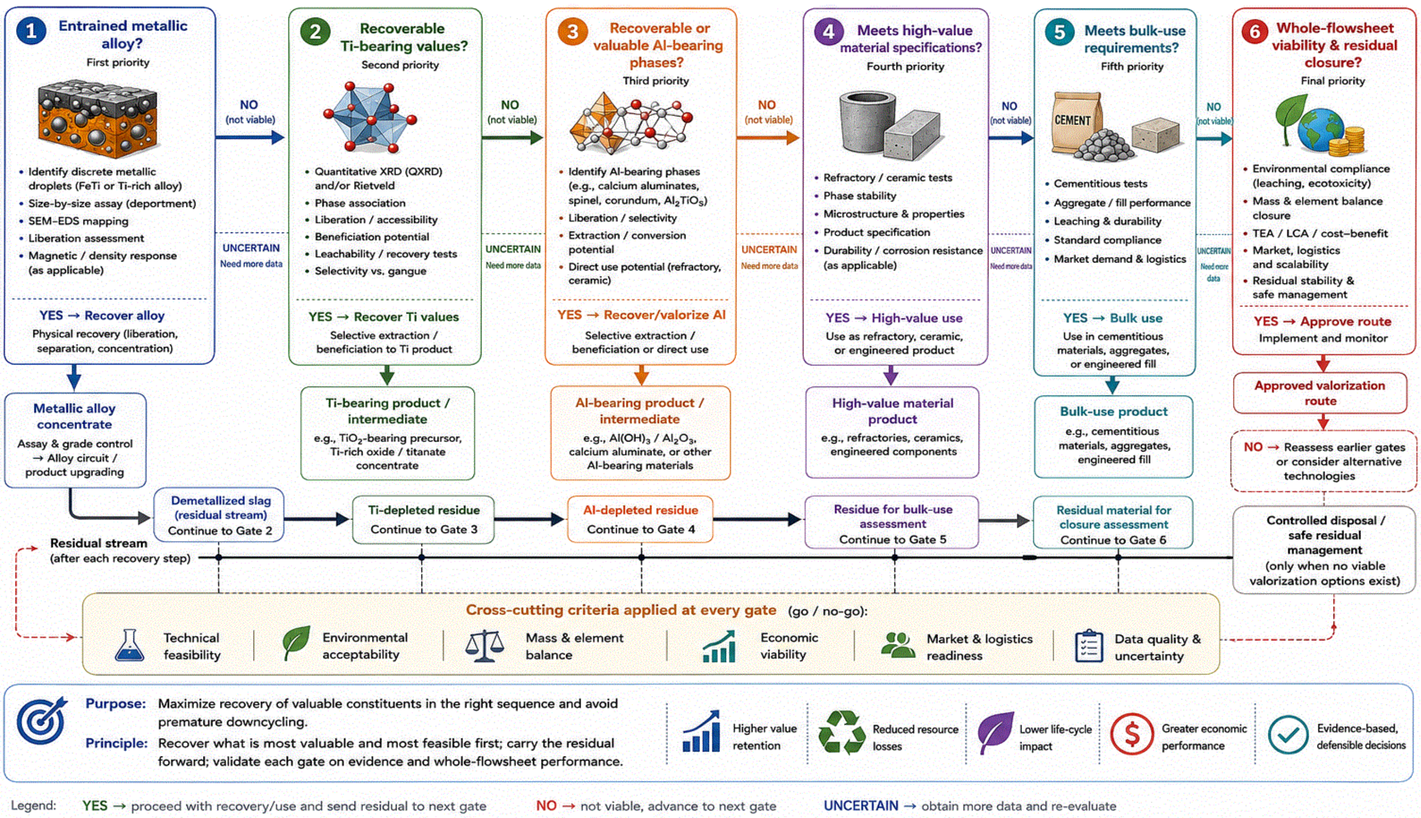


Figure 6. Operational six-gate decision framework for selecting a valorization route for slags generated during aluminothermic titanium processing.

Note. Author-developed decision framework integrating mineralogy, recovery, materials performance, environmental acceptance, and industrial readiness (Feng et al., 2023; C. Li et al., 2025; Nkosi et al., 2026; Tao et al., 2022; Zhang et al., 2026).

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume X Issue VIII August 2026

The relative position of the main valorization routes across value preservation, energy and reagent demand, residue risk, market or maturity, and evidence confidence is compared qualitatively in Table 8.

Table 8. Qualitative multicriteria screening of Ti-aluminothermic slag valorization pathways.

Route	Relative value preservation*	Energy/ reagents	Residue risk	Market/maturity	Evidence confidence
Entrained FeTi recovery	Very high	Low–moderate	Low	Established unit operations; slag-specific validation	Moderate
Residual Ti recovery	High	Moderate–high	Moderate	Large Ti market; chemistry often laboratory-scale	Moderate
Al/Al_2O_3 recovery	High	Moderate–high	Moderate–high	Attractive only with favorable Al mineralogy/purity	Low–moderate
Refractory/ advanced ceramics	High	Moderate thermal	Low–moderate	Higher value; smaller, specification-sensitive market	Moderate
Cementitious use	Moderate–low	Low–moderate	Low if stable	Large market; risk of downcycling	Low–moderate
Aggregate/ geotechnical	Low	Low	Requires leaching/volume stability	Very large market; lowest value	Low
Disposal	None	Low process / recurring liability	Highest long-term liability	No product value	High (liability basis)

Note. Author-developed multicriteria synthesis based on the cited literature (Cai et al., 2022; J. Li et al., 2022; Y. Li, Zhao, et al., 2022; Nkosi et al., 2026; Sparis et al., 2024; Tao et al., 2022; Zhang et al., 2026).

Note. *Value-preservation, energy/reagent, and residue-risk categories are qualitative comparative descriptors derived from the reviewed evidence; they are not substitutes for site-specific TEA, LCA, market analysis, or product qualification.

The measurement and decision requirements associated with each stage of the framework are operationalized in Table 9, which identifies the minimum evidence, decision variable, pass outcome, and action when a gate is not demonstrated.

Table 9. Operationalization of the six-gate slag-valorization framework.

Gate	Minimum evidence	Decision variable	Pass outcome	If not demonstrated
1. Entrained metal	Bulk chemistry; polished-section SEM–EDS; image analysis; size-by-size metal accounting	Recoverable FeTi inventory and liberation size	Recover FeTi by staged crushing + physical separation	Proceed to Gate 2 without assuming slag Ti is metallic
2. Residual Ti	QXRD/Rietveld; automated mineralogy where available; beneficiation/leach tests	Ti host phase, liberation, recovery and defined product form	Select beneficiation, selective decomposition or Ti-product route	Proceed to Gate 3; avoid forcing refractory Ti into aggressive chemistry

Gate	Minimum evidence	Decision variable	Pass outcome	If not demonstrated
3. Aluminum	Al host-phase association; selective dissolution/direct-use tests; impurity balance	Recoverable Al or functional Al-bearing phase	Al/Al_2O_3 product or direct ceramic/refractory use	Proceed to Gate 4
4. High-value material	Refractory/ceramic composition, thermal, mechanical and corrosion tests	Compliance with target product specification and batch variability	Qualify higher-value material product	Proceed to Gate 5
5. Bulk use	Cement/aggregate performance, volume stability, leaching and market-capacity check	Technical acceptance plus realistic local absorption	Select cementitious/aggregate route	Proceed to Gate 6 with disposal/redesign option
6. Closure	Complete mass/energy balance; product/residue leaching; TEA; LCA; residue destination	Regulatory/environmental closure plus site-specific economic feasibility	Implement only after technical qualification and positive/acceptable economic case	Redesign upstream gates, change product target, or select controlled disposal

Note. The framework uses measurable decision variables rather than universal numerical thresholds; plant-specific cutoffs must be set based on product specifications, regulations, market capacity, and site economics.

Worked applications of the six-gate framework

To demonstrate how the framework behaves in practice without overstating validation, it was retrospectively applied to two published real-material aluminothermic cases already included in the evidence base. These are worked applications, not new experiments or industrial validation. A gate is marked “not demonstrated” whenever the cited study does not report the required evidence; missing information is not inferred from another slag system.

Case A—bauxite-residue/ilmenite aluminothermy (Sparis et al., 2024; D2, laboratory-real feed). For the experimentally produced 50:50 bauxite-residue/ilmenite condition, the reported slag contained 70.20 wt% Al_2O_3, 12.24 wt% CaO, 5.04 wt% Na_2O, 2.12 wt% SiO_2, 3.47 wt% Fe_2O_3, and 2.51 wt% TiO_2, while a commercial-grade FeTi alloy was obtained at laboratory scale. The case is deliberately informative because the bulk composition appears attractive for Al-bearing or cement-related use, yet the published data do not by themselves establish residual-Ti mineralogy, entrained-metal liberation, product qualification, environmental closure, or site-specific economics.

Case B—controllable aluminothermic processing of vanadium-extraction tailings (Wu et al., 2026; D1/D2, laboratory-real residue). At 950 °C for 60 min under Ar, the selective route produced a Ti-rich slag containing 63.27 wt% TiO_2, with reported Fe and Ti recoveries of 83.78% and 96.58%, respectively; the deep-reduction route, after TiO_2 supplementation, produced FeTi40B containing 40.9 wt% Ti. This case demonstrates controllable Fe/Ti partitioning on a real residue but does not report the full set of liberation, downstream product-qualification, long-duration pilot, TEA, and LCA data required for industrial closure.

Table 10 applies each gate to these two cases and makes the stopping points explicit rather than assuming that a successful metallurgical experiment constitutes a complete valorization route.

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume X Issue VIII August 2026

Table 10. Worked application of the six-gate framework to two published real-material aluminothermic cases.

Gate	Case A: Sparis et al. (2024)	Case B: Wu et al. (2026)
1. Entrained metal	Partial: bulk alloy production demonstrated, but entrained-metal inventory and liberation in the slag were not quantified.	Partial: Fe partitioning/recovery demonstrated, but size-by-size liberation and physical recovery of residual metallic inclusions were not reported.
2. Residual Ti	Not demonstrated: 2.51 wt% TiO_2 reported in the slag, but Ti host phase, liberation, and recoverable Ti product were not established.	Partial/pass for concentration: 63.27 wt% TiO_2 slag and high Ti recovery were demonstrated; a qualified downstream Ti product and full residue closure were not.
3. Aluminum	Not demonstrated as a recovered product: 70.20 wt% Al_2O_3 is favorable inventory, but phase-selective Al recovery or direct Al-phase qualification was not tested.	Not demonstrated: the Al-bearing matrix affects reduction behavior, but no Al recovery or direct Al-bearing product was qualified.
4. High-value material	Not demonstrated: composition suggests potential, but refractory/ceramic product tests were not part of the case.	Not demonstrated in this study: the Ti-rich slag was a process product, not a qualified refractory/ceramic product.
5. Bulk use	Partial/conceptual: cement compatibility was a design objective, but route-specific product qualification and local market absorption remain required.	Not demonstrated.
6. Closure	Not passed: laboratory technical feasibility is supported, but complete route-specific TEA/LCA, environmental testing, and industrial variability data are absent.	Not passed: controllable partitioning is technically demonstrated, but commercial feasibility requires pilot continuity, reagent/energy closure, TEA/LCA, environmental testing, and market analysis.

Note. "Partial" indicates that a study reports evidence relevant to a gate but does not satisfy all minimum evidence listed in Table 9. These worked applications are diagnostic examples, not validation of universal numerical thresholds.

Evidence strength and the technical–economic boundary

Table 11 makes the strength of the major synthesis claims explicit. The indicator is deliberately asymmetric: strong mechanistic transfer evidence can support a candidate mechanism without upgrading a route to direct aluminothermic proof. Likewise, a successful laboratory product can establish technical feasibility while economic feasibility remains unproven. In this review, Gates 1–5 primarily screen technical and product feasibility; Gate 6 is the closure gate and cannot be passed by technical performance alone. Economic feasibility requires a site-specific comparison of revenues or avoided liabilities against capital, energy, reagents, recycle, labor, maintenance, residue treatment, logistics, market absorption, and uncertainty.

Table 11 summarizes the dominant evidence supporting the principal conclusions and the maximum claim that the current evidence can defensibly sustain.

Table 11. Evidence-strength indicator for major synthesis conclusions.

Major conclusion	Dominant evidence	Confidence	Scope of justified claim
Mineralogy and element deportment are more decision-relevant than bulk Al_2O_3 alone.	D1/D2 + phase-matched T1/T2	Moderate	Supported as a general screening principle; quantitative thresholds remain slag-specific.

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume X Issue VIII August 2026

Liberatable FeTi/metal should be assessed before reagent-intensive treatment of the oxide matrix.	D2 + separation mechanisms; limited D1	Moderate	Strong value-preservation logic; plant cutoffs depend on liberation, grade, and economics.
Hydrometallurgical Ti routes from other Ti slags require phase/redox matching before transfer to aluminothermic slag.	Predominantly T1/T2	Low–moderate for direct transfer	Mechanisms and candidate reagents are supported; equivalent recovery from real aluminothermic slag is not demonstrated.
Refractory/advanced-ceramic use is the strongest direct materials-valorization branch in the corpus.	D1 laboratory-real ferrotitanium slag	Moderate	Technical material feasibility is supported; batch variability, market scale, and route economics remain case-specific.
Validation of the six-gate framework as an industrial decision model.	Author synthesis informed by D1–T2/C	Low as a validated model	Use only as a screening/hypothesis-generating framework until validated with real-slag mass balance, pilot data, TEA/LCA, and environmental closure.

Note. Confidence refers to evidential support for the stated claim, not study quality. D1 = real aluminothermic slag; D2 = direct aluminothermic feed/alloy evidence with slag relevance; T1 = phase-matched non-aluminothermic Ti-slag transfer; T2 = synthetic/model/mechanistic analog; C = contextual evidence.

Critical research gap

The central gap is not a lack of individual recovery technologies; it is the absence of integrated demonstrations on real aluminothermic Ti slags that connect hot-stage process control to phase-resolved characterization, physical metal recovery, selective Ti/Al processing, final-residue management, and product qualification with closed Ti–Al–Fe–Ca balances, energy and reagent accounting, TEA, LCA, and environmental testing. The worked cases in Table 10 illustrate this discontinuity: promising technical transformations can be demonstrated while later gates remain open. The priority is therefore systems integration and validation rather than another isolated extraction-percentage or single-formulation study.

Limitations of the review

Several limitations constrain the strength of inference. First, the original database exports, duplicate counts, exclusion logs, exact query dates, and screening history were not retained; the discovery-stage corpus therefore cannot be independently reconstructed, and the review should not be interpreted as exhaustive. The 20 August 2026 verification search improves currency and bibliographic checking but does not repair that reproducibility gap. Second, the evidence base is heterogeneous, with substantially stronger direct evidence for aluminothermic alloy production and ferrotitanium-slag ceramics than for hydrometallurgical treatment of real aluminothermic slag. Third, D1/D2/T1/T2/C and technology-scale descriptors are author-applied transparency tools rather than reliability-tested risk-of-bias grades, and no inter-reviewer agreement statistic is available. Fourth, quantitative outcomes use incompatible denominators, feed compositions, phase assemblages, and product definitions, precluding defensible pooled effect estimates. Fifth, route-specific mass balances, energy and reagent data, TEA, LCA, environmental closure, batch-variability assessment, and long-duration pilot evidence remain sparse. Finally, the worked applications in Table 10 test the logic of the gates against published cases but do not validate predictive thresholds or industrial economics. The six-gate framework should therefore be used as a screening and hypothesis-generating tool until prospectively validated on actual slag streams.

CONCLUSIONS AND RESEARCH PRIORITIES

Conclusions

Aluminothermic titanium processing should be evaluated as a coupled alloy–slag manufacturing system. Across the evidence base, the most defensible general conclusion is that slag value cannot be inferred from bulk Al_2O_3 alone: mineralogy, Ti/Al deportment, entrained metal, cooling history, and separability control which routes

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume X Issue VIII August 2026

remain technically credible. This conclusion is supported by direct aluminothermic studies together with phase-matched slag evidence, but numerical decision thresholds remain material-specific.

The default screening priority is to assess physically liberatable FeTi or other metallic values first, then residual Ti, then Al recovery or direct Al-bearing phase use, followed by higher-value refractory/ceramic products and finally bulk applications. The strongest direct materials evidence is for real ferrotitanium-slag refractory/ceramic use; hydrometallurgical Ti recovery from real aluminothermic slag remains much less directly demonstrated and should be transferred from other Ti slags only after phase and redox matching. The hierarchy preserves optionality but is not a universal economic ranking.

Bulk construction applications remain important for volume closure after higher-value opportunities have been screened. The two worked applications show why technical and economic feasibility must remain separate: a slag may meet a compositional, recovery, or material-performance gate while still lacking the mass/energy closure, environmental qualification, market capacity, and site-specific TEA/LCA required for implementation. The six-gate framework is therefore a screening and hypothesis-generating tool, not a validated industrial decision model. Its strongest future test will be a prospective, integrated demonstration on real aluminothermic slag from charge design through saleable products and environmentally acceptable residual streams.

Research priorities

Future research should prioritize complete Ti–Al–Fe–Ca mass balances; quantitative XRD/Rietveld and automated mineralogy; size-resolved entrained-alloy accounting; controlled cooling-rate studies; sequential FeTi → Ti → Al recovery on real slags; deliberate engineering of Al_2TiO_5, Ti_2O_3–Al_2O_3, calcium-aluminate, and spinel-bearing co-products; batch-to-batch variability; and pilot-scale metal–slag separation. Each proposed route should report energy per tonne of slag, reagent consumption and recycle, water demand, product yield and specification, residue generation and leachability, capital/operating cost basis, market-capacity assumptions, sensitivity analysis, and LCA functional unit/allocation. The most valuable next experiment is not one that maximizes a single extraction percentage, but one that demonstrates a closed, phase-informed, economically plausible flowsheet from aluminothermic charge to saleable alloy, saleable slag-derived product, and environmentally acceptable residual stream.

Declarations

Funding: This review received no external funding.

Competing interests: The author declares no competing interests.

Author contributions: Antonio Clareti Pereira: Conceptualization, methodology, literature verification, evidence synthesis, visualization, writing—original draft, and writing—review and editing.

Data availability: No new experimental dataset was generated. The evidence base consists of the publications cited in the reference list.

REFERENCES

1. Bhalla, A., & Shukla, A. K. (2022). Overview of thermodynamics concepts in production of some ferroalloys (ferrochrome, ferromanganese, ferrotitanium and ferrovanadium). In Proceedings of the International Conference on Enhanced Use of Thermodynamic Data in Pyrometallurgy Teaching and Research (THANOS 2022) (pp. 11–22). The Southern African Institute of Mining and Metallurgy.
2. Bian, Z.-Z., Feng, Y.-L., & Li, H.-R. (2020). Extraction of valuable metals from Ti-bearing blast furnace slag using ammonium sulfate pressurized pyrolysis–acid leaching processes. Transactions of Nonferrous Metals Society of China, 30(10), 2836–2847. https://doi.org/10.1016/S1003-6326(20)65425-5
3. Cai, Y., Song, N., Yang, Y., Sun, L., Hu, P., & Wang, J. (2022). Recent progress of efficient utilization of titanium-bearing blast furnace slag. International Journal of Minerals, Metallurgy, and Materials, 29(1), 22–31. https://doi.org/10.1007/s12613-021-2323-1

4. Chadirji-Martinez, K., Hudon, G., Chernikov, R., Heredia, E., Feng, R., Crawford, A., & Pan, Y. (2025). Thorium speciation in titania slag: Implications for environmental remediation and valorisation. Mineralogical Magazine, 89(1), 113–126. https://doi.org/10.1180/mgm.2024.69
5. Cheng, C., Dou, Z.-H., Zhang, T.-A., & Song, Y.-L. (2021). Multistage desulfurization mechanism to reduce the sulfur content of high-ferrotitanium prepared by the thermite method. Rare Metals, 40(8), 2313–2319. https://doi.org/10.1007/s12598-020-01583-2
6. Cheng, Q., Zhang, Z., Xing, X., Zheng, J., & She, Y. (2023). Effect of MgO/Al_2O_3 on viscosity and thermodynamic properties of high-titanium slag containing chlorine. Minerals, 13(3), Article 444. https://doi.org/10.3390/min13030444.
7. Cheng, S., Vaughan, J., Wang, G., Ma, X., Lyu, X., & Peng, H. (2026). Slag to product: Unlocking titanium-bearing slag value via selective leaching of amorphous titanium phase. Minerals Engineering, 235(Part 1), Article 109846. https://doi.org/10.1016/j.mineng.2025.109846
8. Choi, J.-H., Chang, H., Ryu, T., Nam, C.-W., & Kim, B.-S. (2020). Investigating the aluminothermic process for producing ferrotitanium alloy from ilmenite concentrate. Metals, 10(11), Article 1493. https://doi.org/10.3390/met10111493
9. Ding, M. (2024). Titanium-containing blast furnace slag produced titanium-silicon-aluminum alloy by aluminothermic reduction. Multipurpose Utilization of Mineral Resources, 45(6), 54–58, 66. https://doi.org/10.3969/j.issn.1000-6532.2024.06.009
10. Dmitriev, A. N., Smorokov, A. A., Kantaev, A. S., Nikitin, D. S., & Vit'kina, G. Yu. (2022). Fluoroammonium method for titanium slag processing. Steel in Translation, 52(1), 81–86. https://doi.org/10.3103/S0967091222010107
11. Thikkandy Edathil, S., Anil, A. N., Jayapalan, V., & Kalidoss, J. (2024). Sustainable process for preparation of Ti rich alloy from acidic TiO_2 sludge. Transactions of the Indian Institute of Metals, 77(11), 3605–3613. https://doi.org/10.1007/s12666-024-03404-x
12. Fan, G., Wang, M., Dang, J., Zhang, R., Lv, Z., He, W., & Lv, X. (2021). A novel recycling approach for efficient extraction of titanium from high-titanium-bearing blast furnace slag. Waste Management, 120, 626–634. https://doi.org/10.1016/j.wasman.2020.10.024
13. Fan, W., Peng, Z., Yang, F., Bai, H., & Yi, L. (2026). Mechanism of silica-mediated phase separation for selective crystallization and enrichment of rutile in titanium-bearing electric arc furnace slag. Journal of Environmental Chemical Engineering, 14(3), Article 122835. https://doi.org/10.1016/j.jece.2026.122835
14. Feng, E., Gao, D., Wang, Y., Yu, F., Wang, C., Wen, J., Gao, Y., Huang, G., & Xu, S. (2023). Sustainable recovery of titanium from secondary resources: A review. Journal of Environmental Management, 339, Article 117818. https://doi.org/10.1016/j.jenvman.2023.117818
15. 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
16. Gao, Z., Cheng, G., Yang, H., & Xue, X. (2021). Heating-assisted preparation of ferrotitanium to recover valuable elements of ilmenite and reduce aluminum consumption. JOM, 73(5), 1321–1327. https://doi.org/10.1007/s11837-021-04591-4
17. 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
18. Gu, H., Cao, J., Wu, J., Xu, M., & Ma, W. (2022). Recovery of Ti-bearing blast furnace slag and diamond wire saw silicon powder waste by alloying and electromagnetic separation technique. Journal of Cleaner Production, 359, Article 132080. https://doi.org/10.1016/j.jclepro.2022.132080
19. Gulyaeva, R. I., Pikulin, K. V., Mansurova, A. N., Pikalov, S. M., & Leont'ev, L. I. (2023). Phase formation during aluminothermic reduction of titanium from its oxides with the anatase and rutile structures. Inorganic Materials, 59(2), 134–144. https://doi.org/10.1134/S0020168523020061
20. Guo, J., Zhou, H., Hou, Y., Zhang, S., Dang, J., & Lv, X. (2024). Thermophysical properties, crystallization behavior and structure of $CaO–SiO_2–MgO–Al_2O_3–TiO_2–FeO$ slag with varying TiO_2 contents. Ceramics International, 50(20, Part B), 39069–39079. https://doi.org/10.1016/j.ceramint.2024.07.273

21. Guo, Y., Jing, J., Wang, S., Chen, F., Yang, L., & Qiu, G. (2024). Effect of CaO/MgO on rheological properties and structure of $CaO–MgO–SiO_2–Al_2O_3$–50% TiO_2 slag with SiO_2/Al_2O_3 = 1.0. Ceramics International, 50(20, Part A), 38732–38740. https://doi.org/10.1016/j.ceramint.2024.07.244
22. Guo, Z., Chen, X., Zhu, D., Pan, J., Yang, C., & Li, S. (2026). Integrated valorization of vanadium–titanium magnetite for recovery of vanadium-bearing molten iron and rutile-rich TiO_2 product. Metals, 16(8), Article 888. https://doi.org/10.3390/met16080888
23. Gupta, A. K., Aula, M., Pihlasalo, J., Mäkelä, P., Huttula, M., & Fabritius, T. (2021). Preparation of synthetic titania slag relevant to the industrial smelting process using an induction furnace. Applied Sciences, 11(3), Article 1153. https://doi.org/10.3390/app11031153
24. Gupta, A. K., Aula, M., Sreenivasan, H., Mäkelä, P., Huttula, M., & Fabritius, T. (2022). Study of synthetic titania slags demonstrating characteristics similar to high titania ilmenite slag. Minerals, 12(3), Article 386. https://doi.org/10.3390/min12030386
25. Han, Y., Dou, Z., & Zhang, T. (2025). Distribution regularity and mechanism of non-titanium components in titanium-rich slag. Ceramics International, 51(26, Part A), 47801–47808. https://doi.org/10.1016/j.ceramint.2025.08.039.
26. Janakiram, V., Jayasankar, K., Babu, T. D., Bhargava, N. R. M. R., & Mukherjee, P. S. (2020). An innovative approach of recycling aluminium scrap for ferrotitanium production. Journal of The Institution of Engineers (India): Series D, 101(1), 7–13. https://doi.org/10.1007/s40033-020-00218-1
27. Jiang, H., Zhang, T.-A., & Dou, Z.-H. (2026). Preparation of γ-TiAl alloys via self-propagating aluminothermic reduction–slag washing refining coupled with vacuum arc remelting. Materials, 19(8), Article 1650. https://doi.org/10.3390/ma19081650
28. Jing, J., Guo, Y., Wang, S., Chen, F., Yang, L., & Qiu, G. (2022). Recent progress in electric furnace titanium slag processing and utilization: A review. Crystals, 12(7), Article 958. https://doi.org/10.3390/cryst12070958
29. Jing, J., Guo, Y., Wang, S., Chen, F., Yang, L., Yang, J., Xu, F., & Yu, L. (2024). Melting properties and phase-composition transformations of Ti-bearing electric-furnace slags in the $CaO–SiO_2–MgO–Al_2O_3$–50% TiO_2 system. Metals and Materials International, 30(8), 2045–2056. https://doi.org/10.1007/s12540-024-01630-y
30. Jing, J., Wang, S., Guo, Y., Li, G., Chen, F., & Yang, L. (2023). Phase equilibria of Ti-bearing electric furnace slags in the $CaO–MgO–SiO_2$–13%Al_2O_3–50%TiO_2 system. JOM, 75(12), 5160–5166. https://doi.org/10.1007/s11837-023-06078-w
31. Jing, J.-F., Guo, Y.-F., Wang, S., Chen, F., Yang, L.-Z., & Qiu, G.-Z. (2026). Phase composition of slag–iron interface and elemental distribution behavior between hot metal and Ti-bearing electric furnace slags. Transactions of Nonferrous Metals Society of China, 36(4), 1320–1334. https://doi.org/10.1016/S1003-6326(25)67033-6
32. Jing, J.-F., Wang, S., Guo, Y.-F., Chen, F., & Yang, L.-Z. (2024). Phase equilibria of Ti-bearing electric furnace slags in air at 1400 °C in $CaO–MgO–SiO_2$–13 wt pct Al_2O_3–50 wt pct TiO_2 system. Metallurgical and Materials Transactions B, 55(5), 3097–3106. https://doi.org/10.1007/s11663-024-03161-8
33. Kim, D. H., Heo, J. H., Park, H. S., Kim, J. K., & Park, J. H. (2020). Improving the production efficiency of high-titania slag in Ti extraction process: Fluxing effect on formation of pseudobrookite. Scientific Reports, 10, Article 6530. https://doi.org/10.1038/s41598-020-63532-4
34. Kumai, E., Yang, F., & Xiang, L. (2024). Thermodynamic and experimental studies of selective decomposition of diopside in Ti-bearing blast furnace slag. ACS Omega, 9(34), 36635–36639. https://doi.org/10.1021/acsomega.4c05004
35. Lee, J. H., Nersisyan, H. H., Lim, K.-S., Kim, W.-B., & Choi, W.-S. (2021). Combustion-aluminothermic reduction of TiO_2 to produce titanium low oxygen suboxides. Metallurgical and Materials Transactions B, 52(6), 4012–4022. https://doi.org/10.1007/s11663-021-02316-1
36. Lei, H., Tan, C., Fan, G., Huang, D., Ding, X., & Dang, J. (2021). The crystallization behavior of $TiO_2–CaO–SiO_2–Al_2O_3$–MgO pentabasic slag with a basicity of 1.1–1.4. Crystals, 11(6), Article 583. https://doi.org/10.3390/cryst11060583
37. 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

38. Li, J., Yu, J., Zhao, H., Sang, S., Zhang, H., & Wang, Y. (2022). Phase stability and enhanced mechanical properties of ferro-titanium slag to aluminum titanate ceramics. Materials Letters, 324, Article 132755. https://doi.org/10.1016/j.matlet.2022.132755
39. Li, W., Qiu, J., Liu, C., & Jiang, M. (2024). Experimental investigation of the phase equilibria of CaO–Al_2O_3–TiO_2 slag system at 1500 °C with $p(O_2) = 10^{-3}$ atm. Ceramics International, 50(4), 6068–6078. https://doi.org/10.1016/j.ceramint.2023.11.304
40. Li, Y., & Yan, B. (2023). A novel approach for pre-concentrating titanium from Ti-bearing blast furnace slag. Separation Science and Technology, 58(9), 1679–1688. https://doi.org/10.1080/01496395.2023.2198104
41. Li, Y., Zhang, H., Zhao, H., Yu, J., Feng, L., & Liu, Y. (2022). Preparation and characterization of Al_2O_3-SiC-C castables using ferrotitanium slag: Structural commonalities between titanium–alumina slag and calcium alumino-titanate. Journal of the Australian Ceramic Society, 58(5), 1423–1432. https://doi.org/10.1007/s41779-022-00742-1 .
42. Li, Y., Zhao, H., Ma, J., Wang, Y., Zhang, H., Yu, J., Feng, L., & Liu, Y. (2022). Evaluation of remelting low-fluxing ferrotitanium slag as a potential refractory raw material: Thermal characteristics and stability. Ceramics International, 48(8), 11192–11198. https://doi.org/10.1016/j.ceramint.2021.12.339
43. Liao, J., & Zhao, B. (2022). Phase equilibrium studies of titanomagnetite and ilmenite smelting slags. International Journal of Minerals, Metallurgy and Materials, 29(12), 2162–2171. https://doi.org/10.1007/s12613-021-2376-1
44. Liu, Y., Chen, X., Mao, S., Xiao, Y., & Li, J. (2024). Extraction of valuable metals from titanium-bearing blast furnace slag by acid leaching. Journal of Wuhan University of Technology-Materials Science Edition, 39(2), 376–385. https://doi.org/10.1007/s11595-024-2893-7
45. Liu, Y., Zhao, B., He, G., Liu, F., Liu, Q., Miao, W., Qu, T., Yang, B., Liu, D., & Dong, Z. (2026). One-step separation of magnesium and calcium from high-titanium slag by pressurized oxidation acid leaching. Journal of Sustainable Metallurgy, 12(4), 3974–3990. https://doi.org/10.1007/s40831-026-01554-4
46. Ma, H., Jiao, K., Zhang, J., Zong, Y., Zhang, J., & Meng, S. (2021). Viscosity of CaO–MgO–Al_2O_3–SiO_2–TiO_2–FeO slag with varying TiO_2 content: The effect of crystallization on viscosity abrupt behavior. Ceramics International, 47(12), 17445–17454. https://doi.org/10.1016/j.ceramint.2021.03.061
47. Matinde, E., & Steenkamp, J. D. (2021). Metallurgical overview and production of slags. In N. M. Piatak & V. Ettler (Eds.), Metallurgical slags: Environmental geochemistry and resource potential (pp. 14–58). Royal Society of Chemistry. https://doi.org/10.1039/9781839164576-00014
48. Matsanga, N., Wa Kalenga, M., & Nheta, W. (2025). An overview of thermochemical reduction processes for titanium production. Minerals, 15(1), Article 17. https://doi.org/10.3390/min15010017
49. Myrzakulov, M. K., Dzhumankulova, S. K., Yelemessov, K. K., Barmenshinova, M. B., Martyushev, N. V., Skeeba, V. Y., Kondratiev, V. V., & Karlina, A. I. (2024). Analysis of the effect of fluxing additives in the production of titanium slags in laboratory conditions. Metals, 14(12), Article 1320. https://doi.org/10.3390/met14121320
50. Nababan, D. C., Nuraeni, B. A., Rhamdani, A. R., Pownceby, M. I., & Rhamdhani, M. A. (2026). Metallothermic reduction using aluminum for metal and alloy production. International Materials Reviews. Advance online publication. https://doi.org/10.1177/09506608261467561
51. Nie, W., Wen, S., Liu, D., Hu, T., & Zhang, L. (2023). Innovative application of two-stage sulfuric acid leaching for efficient recovery of Ti from titanium-bearing electric furnace slag. Journal of Environmental Chemical Engineering, 11(1), Article 109174. https://doi.org/10.1016/j.jece.2022.109174
52. Nkosi, S., Goso, X. C., Mokone, T., Petersen, J., & Bungane, T. (2026). Discounted cash flow analysis of a process for vanadium extraction from titaniferous slag. Minerals, 16(4), Article 378. https://doi.org/10.3390/min16040378
53. Oncel, L. (2025). Thermodynamic modeling, metallothermic synthesis, and characterization of ferrotitanium. Materials Testing, 67(2), 240–248. https://doi.org/10.1515/mt-2024-0364
54. Pereira, A. C. (2026a). Liquid-metal droplet coalescence in metallurgical slags: A critical review of interfacial phenomena, slag properties, hydrodynamics, kinetics, and metal recovery. International Journal of Research and Innovation in Social Science, 10(7). https://doi.org/10.47772/IJRISS.2026.100701023

55. 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
56. Piao, R., Yang, S., Ma, L., & Wang, T. (2020). Vacuum electromagnetic levitation melting of Ti–Al based alloy prepared by aluminothermic reduction of acid soluble Ti bearing slag. Metals and Materials International, 26(1), 130–142. https://doi.org/10.1007/s12540-019-00295-2
57. Qu, Y., Xing, L., Gao, M., Zhao, S., Ren, Q., Li, L., & Long, Y. (2024). Progress and prospects for titanium extraction from titanium-bearing blast furnace slag. Materials, 17(24), Article 6291. https://doi.org/10.3390/ma17246291
58. Ren, S., Su, Z., Liu, W., Sun, Y., Li, X., & Yang, J. (2020). Ti_3O_5 and Al_2TiO_5 crystals flotation characteristics from Ti-bearing blast furnace slag: A density functional theory and experimental study. Crystals, 10(9), Article 838. https://doi.org/10.3390/cryst10090838.
59. Samal, S. K., Mishra, B., & Mishra, S. C. (2020). Carboaluminothermic production of ferrotitanium from ilmenite through thermal plasma. Journal of Sustainable Metallurgy, 6(4), 563–575. https://doi.org/10.1007/s40831-020-00292-5
60. Schirmer, T., Achimovičová, M., & Goldmann, D. (2020). Influence of chemical and phase composition in the hydrometallurgical processing of FeTi oxide phases. Hydrometallurgy, 191, Article 105250. https://doi.org/10.1016/j.hydromet.2020.105250
61. Shi, J., Chen, M., Wan, X., Taskinen, P., & Jokilaakso, A. (2020). Phase equilibrium study of the CaO–SiO_2–MgO–Al_2O_3–TiO_2 system at 1300 °C and 1400 °C in air. JOM, 72(9), 3204–3212. https://doi.org/10.1007/s11837-020-04136-1
62. Shi, J., Qiu, Y., Yu, B., Xie, X., Dong, J., Hou, C., Li, J., & Liu, C. (2022). Titanium extraction from titania-bearing blast furnace slag: A review. JOM, 74(2), 654–667. https://doi.org/10.1007/s11837-021-05040-y
63. Song, Y., Dou, Z., Cheng, C., & Zhang, T.-A. (2023). Novel insight into the preparation of Ti-6Al-4V alloy through thermite reduction based on the mass action concentration. Journal of Wuhan University of Technology-Materials Science Edition, 38(3), 652–658. https://doi.org/10.1007/s11595-023-2741-1
64. Song, Y., Dou, Z., Zhang, T.-A., & Liu, Y. (2021). Research progress on the extractive metallurgy of titanium and its alloys. Mineral Processing and Extractive Metallurgy Review, 42(8), 535–551. https://doi.org/10.1080/08827508.2020.1793145
65. Song, Y., Dou, Z., Zhang, T.-A., & Wang, G. (2021). Mechanisms of metal-slag separation behavior in thermite reduction for preparation of TiAl alloy. Journal of Materials Engineering and Performance, 30(12), 9315–9325. https://doi.org/10.1007/s11665-021-06074-8
66. Sparis, D., Lazou, A., Balomenos, E., & Panias, D. (2024). Thermodynamics of aluminothermic processes for ferrotitanium alloy production from bauxite residue and ilmenite. Metals, 14(2), Article 200. https://doi.org/10.3390/met14020200
67. 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
68. Takeda, O., Ouchi, T., & Okabe, T. H. (2020). Recent progress in titanium extraction and recycling. Metallurgical and Materials Transactions B, 51(4), 1315–1328. https://doi.org/10.1007/s11663-020-01898-6
69. Tao, M., Lu, D., Shi, Y., & Wu, C. (2022). Utilization and life cycle assessment of low activity solid waste as cementitious materials: A case study of titanium slag and granulated blast furnace slag. Science of the Total Environment, 849, Article 157797. https://doi.org/10.1016/j.scitotenv.2022.157797
70. Tian, M., Liu, Y., Zhao, W., Wang, L., Chen, D., Zhao, H., Meng, F., Zhen, Y., & Qi, T. (2022). Preparing metatitanic acid from perovskite-type titanium slag using a sulfuric–chloric mixture acid. JOM, 74(3), 1070–1078. https://doi.org/10.1007/s11837-021-05136-5
71. Tian, Z., Chen, L., Song, J., Kang, J., Mao, H., & Qiu, G. (2025). Preparation of Ti-Al alloys by aluminothermic reduction with MgF_2 addition. Rare Metal Materials and Engineering, 54(7), 1678–1686. https://doi.org/10.12442/j.issn.1002-185X.20240346
72. Tian, Z., Zheng, W., Yang, L., Wu, C., Kang, J., Chen, J., & Qiu, G. (2025). Synthesis of titanium-based alloys from spent SCR catalysts: A novel approach. Journal of Materials Research and Technology, 35, 7111–7119. https://doi.org/10.1016/j.jmrt.2025.03.035

73. Vusikhis, A. S., Tyushnyakov, S. N., Udoeva, L. Y., Agafonov, S. N., & Pikulin, K. V. (2024). Viscosity of titanium slag in separating electric melting of a metallized mixture of perovskite and ilmenite concentrates. Rasplavy, (4), 430–441. https://doi.org/10.31857/S0235010624040075
74. Wang, H., Sun, K., Wang, B., Lu, R., & Wu, X. (2023). Effect of mineral phases on the leaching efficiency of Ti slag. Canadian Metallurgical Quarterly, 62(2), 322–329. https://doi.org/10.1080/00084433.2022.2090085
75. Wang, Y., Karasev, A., Park, J. H., & Jönsson, P. G. (2021). Non-metallic inclusions in different ferroalloys and their effect on the steel quality: A review. Metallurgical and Materials Transactions B, 52(5), 2892–2925. https://doi.org/10.1007/s11663-021-02259-7
76. Wang, Z., Zhang, J., Zhao, B., & Liu, Z. (2020). Extraction of titanium resources from the titanium-containing waste slag: Thermodynamic analysis and experimental verification. Calphad, 71, Article 102211. https://doi.org/10.1016/j.calphad.2020.102211
77. Wang, Z., Zhang, L., & Zhang, J. (2025). Smelting and utilization technology of ironsands. Springer Singapore. https://doi.org/10.1007/978-981-95-2868-4.
78. Wu, H., Qin, Y., Yu, X., Cheng, G., Xue, X., Du, H., & Liu, B. (2026). Recycling of vanadium-extraction tailings by controllable aluminothermic reduction process. Journal of Cleaner Production, 571, Article 148759. https://doi.org/10.1016/j.jclepro.2026.148759
79. Xu, R., & Wang, Z. (2024). Thermodynamics property and structure evolution of the TiO_2-containing molten slag with different CaO/SiO_2 ratio and TiO_2 content. Ceramics International, 50(19, Part B), 36773–36781. https://doi.org/10.1016/j.ceramint.2024.07.063
80. Yan, Z., Lv, X., & Li, Z. (2022). Physicochemical properties and structure of titania-containing metallurgical slags: A review. Journal of Iron and Steel Research International, 29(2), 187–206. https://doi.org/10.1007/s42243-021-00678-z
81. Yang, J., Wang, Y., Peng, J., & Di, Y. (2022). Reaction mechanism and kinetics of ferrotitanium preparation by aluminothermic reduction of $CaTiO_3$. Materials Today Communications, 30, Article 102995. https://doi.org/10.1016/j.mtcomm.2021.102995
82. Yang, S., Liu, S., Guo, S., Zhang, T., & Li, J. (2022). Fusion separation of vanadium-titanium magnetite and enrichment test of Ti element in slag. Materials, 15(19), Article 6795. https://doi.org/10.3390/ma15196795
83. You, J., Yang, J., Dong, W., Wang, Y., **Wang, R.**, & Wang, Y. (2024). Preparation of ferrotitanium alloy by aluminothermic reduction of perovskite. Process Safety and Environmental Protection, 187, 305–311. https://doi.org/10.1016/j.psep.2024.04.102
84. Yuan, K., He, S., Yu, B., Qian, S., Wu, X., Li, W., & Zhao, C. (2024). Synergistic leaching of titanium, aluminum, and magnesium components during dilute acid pressure treatment of high-titanium blast furnace slag. Molecules, 29(14), Article 3336. https://doi.org/10.3390/molecules29143336
85. Zai, H., Zhang, C., Li, Z., Wang, R., Ma, E., & Zhang, X. (2025). Extraction of titanium from Ti-bearing blast furnace slag using ammonium sulfate roasting-water leaching enhanced by mechanical activation. Journal of Sustainable Metallurgy, 11(2), 1937–1951. https://doi.org/10.1007/s40831-025-01099-y
86. Zhang, B., Zhang, R., Zhang, T.-A., Dou, Z., Song, S., & Wang, Q. (2026). Microstructure study on viscous flow and crystallization behavior of ultra-high titanium slag induced by amphoteric aluminum ions. Journal of Non-Crystalline Solids, 675, Article 123938. https://doi.org/10.1016/j.jnoncrysol.2025.123938
87. Zhang, F., Zhang, H., Zhao, H., & Xu, J. (2023). Sintering properties and microstructure of Al_2O_3–TiO_2–CaO composite materials based on ferrotitanium slag. Ceramics International, 49(23, Part A), 38256–38263. https://doi.org/10.1016/j.ceramint.2023.09.157
88. Zhang, J., Guo, Y., Wang, S., Chen, F., Zheng, Y., & Yang, L. (2026). Phase-controlled selective separation of titanium from titanium-bearing furnace slag via fluoride leaching: Critical role of $[NH_4^+]/[F^-]$ molar ratio. Hydrometallurgy, 239, Article 106602. https://doi.org/10.1016/j.hydromet.2025.106602
89. Zhang, L.-J., Zhang, Y.-Z., Zhu, W., Ren, Q.-Q., Duan, L.-Y., Cai, X.-B., Zhao, X.-H., Gu, X.-W., & Liu, B. (2026). Review on advances in recycling and utilization of titanium-bearing secondary resources. Journal of Iron and Steel Research International, 33(6), Article 172. https://doi.org/10.1007/s42243-026-01842-z

90. Zhang, R., Wang, Q., Zhang, B., Zhang, T.-A., Dou, Z., & Song, S. (2025). Structural interpretation of viscous flow and crystallization behavior of ultra-high titanium molten slag. Ceramics International, 51(16, Part A), 22277–22286. https://doi.org/10.1016/j.ceramint.2025.02.389
91. Zhang, S., Zheng, K., Jiang, J., Zhang, S., & Xu, G. (2021). Effect of operating parameters on high-temperature selective enrichment and precipitation of titanium component in Ti-bearing blast furnace slag and the precipitation mechanism of perovskite. Journal of Materials Research and Technology, 15, 2686–2696. https://doi.org/10.1016/j.jmrt.2021.09.106
92. Zhang, Y., Lei, Y., Ma, W., Shi, Z., Chen, Q., Li, Z., & Wang, C. (2022). A green approach for simultaneously preparing Ti_5Si_3 and Ti_5Si_4–$TiAl_3$ alloys using spent SCR catalyst, Ti-bearing blast furnace slag, and Al alloy scrap. Chemical Engineering Journal, 430(Part 2), Article 132916. https://doi.org/10.1016/j.cej.2021.132916
93. Zhang, Y., Sun, L., Lei, Y., Ma, W., & Li, Z. (2021). Corrosion behavior of carbon, Al_2O_3, and MgO refractories during the preparation of a Ti–Si–Al alloy via the aluminothermic reduction of a Ti-bearing blast-furnace slag. Ceramics International, 47(13), 18044–18052. https://doi.org/10.1016/j.ceramint.2021.03.120
94. Zheng, F., Guo, Y., Chen, F., Wang, S., Zhang, J., Yang, L., & Qiu, G. (2021). Fluoride leaching of titanium from Ti-bearing electric furnace slag in [NH_4^+]–[F^-] solution. Metals, 11(8), Article 1176. https://doi.org/10.3390/met11081176
95. Zheng, Q., Li, Y., Ma, C., Sun, J., & Gao, Y. (2023). Novel Ti_2O_3–Al_2O_3 raw materials with controllable Ti_2O_3 content from the aluminothermic reduction of ilmenite. Ceramics International, 49(19), 31124–31130. https://doi.org/10.1016/j.ceramint.2023.07.057
96. Zheng, Q., Li, Y., Ma, C., Wu, X., Li, H., & Sun, J. (2022). A novel dense Al_2O_3–Ti_2O_3 slag synthesized while ferro-titanium alloy making. Journal of Asian Ceramic Societies, 10(1), 150–157. https://doi.org/10.1080/21870764.2022.2025662
97. Zhou, L., Peng, T., Sun, H., & Wang, S. (2022). Thermodynamics analysis and experiments on Ti-bearing blast furnace slag leaching enhanced by sulfuric acid roasting. RSC Advances, 12(54), 34990–35001. https://doi.org/10.1039/D2RA06237B
98. Zhou, Y., Qiu, G., Jing, J., Zheng, F., Wang, S., Chen, F., & Guo, Y. (2022). A novel process for preparation Ti-rich material from modified electric furnace titanium slag by phase deconstruction method. The Chinese Journal of Process Engineering, 22(5), 651–659. https://doi.org/10.12034/j.issn.1009-606X.221137
99. Zhu, W., Ren, Q., Cai, S., Li, J., Li, L., Duan, L., Zeng, Y., Wang, Y., & Liu, B. (2026). Crystallization behavior of CaO–SiO_2–Al_2O_3–MgO–TiO_2–FeO slag with different CaO/SiO_2 ratios. Materials, 19(8), Article 1574. https://doi.org/10.3390/ma19081574.