JIRRS
Journal International Review of Research Studies

Received: 17/08/2026 - **Accepted:** 17/09/2026
Vol: 01.09
DOI: 10.66104/qa1tk476
Pages: 1-48

From Vanadium–Titanium Magnetite to Fe–C–V Alloys: A Critical Review of Vanadium-Bearing Pig Iron Production, Vanadium Partitioning, Refining, and Metallurgical Applications

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Abstract

Vanadium-bearing pig iron and vanadium-bearing hot metal are usually treated as transient intermediates in routes that selectively oxidize vanadium into converter slag before producing V_2O_5 or ferrovanadium. That interpretation holds for established extraction chains but is incomplete for modern Fe–V–Ti systems, where the same Fe–C–V phase may also be a deliberately produced metallurgical resource. This critical review evaluates that broader decision space from vanadium–titanium magnetite and secondary Fe–V residues through beneficiation, reduction, smelting, metal–slag partitioning, refining, and final metallurgical use. Evidence is separated by both relevance to direct Fe–C–V utilization and demonstration maturity, preventing laboratory possibility, industrial operability, and downstream alloy performance from being treated as equivalent evidence. Particular attention is given to oxygen potential, temperature, slag basicity and FeO/TiO_2 chemistry, carbon activity, viscosity, metal-droplet coalescence, impurity control, and hydrogen-assisted reduction. The review proposes vanadium destination engineering as a unifying framework in which the preferred route places vanadium in the phase that maximizes useful final-product utilization rather than first-stage recovery alone. Direct Fe–C–V use is technically plausible, especially for cast-iron and wear-resistant applications, but the evidence remains predominantly indirect because few studies trace deliberately produced V-bearing pig iron through an industrial receiving melt to final properties. True scale-up is therefore defined as preservation of a multivariable performance vector encompassing feed representativeness, reduction behavior, metal and slag quality, physical separation, energy, carbon, impurity control, and stable operation. Hydrogen-assisted routes can reduce direct fossil-carbon demand, but life-cycle greenhouse-gas benefits depend on hydrogen origin, electricity, pellet preparation, smelting, Ti-slag upgrading, and the downstream vanadium destination. Key gaps remain end-to-end application validation, continuous-scale operation, and route-comparable techno-economic and life-cycle evidence.

Keywords: vanadium–titanium magnetite; vanadium-bearing pig iron; reduction–smelting; metal–slag partitioning; hydrogen metallurgy; vanadium destination engineering

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Highlights

- Vanadium-bearing pig iron should be evaluated as either an extraction intermediate or a destination-specific Fe–C–V resource.
- Vanadium recovery depends on both chemical partitioning and physical metal–slag separation; total slag V alone can conflate these loss modes.
- Hydrogen-assisted reduction can lower direct fossil-carbon demand but may alter metallic-domain morphology and downstream Fe/V/Ti separability.
- True scale-up requires preservation of a coupled performance vector, not reproduction of metal grade or first-stage vanadium recovery alone.

1. Introduction

1.1 Strategic context and the problem with a single-route definition

Vanadium is a strategically important alloying and functional element whose largest established use remains in ferrous metallurgy, while catalysts, titanium alloys, chemical products, and redox-flow batteries broaden its demand base. Vanadium–titanium magnetite (VTM) is one of the most important primary resource classes because iron, vanadium, and titanium occur in a tightly coupled mineralogical system. The resulting flowsheets therefore cannot be optimized by considering vanadium recovery independently from ironmaking, titanium rejection or recovery, slag behavior, carbon demand, and final-product specifications (Gilligan & Nikoloski, 2020; Petranikova et al., 2020; Wang et al., 2024).

The conventional industrial logic is well known: VTM is reduced and smelted to produce vanadium-bearing hot metal; the hot metal is then selectively oxidized to transfer vanadium into a V-rich slag; that slag is subsequently processed to produce vanadium chemicals and ferrovanadium. This sequence has created a durable industrial paradigm in which vanadium in hot metal is interpreted mainly as an intermediate inventory that should eventually be oxidized out of the metal (Lee et al., 2021; Qiu et al., 2026; Yang & Yang, 2024).

That paradigm is increasingly incomplete. Recent work has demonstrated deliberate production of V-bearing metallic products through electric smelting, sodium-assisted smelting, hydrogen-assisted reduction followed by smelting, and direct valorization of steelmaking and non-ferrous slags. In these routes, the Fe–C–V phase may contain enough vanadium to be metallurgically useful before conventional V_2O_5/FeV manufacture. The critical question is therefore not simply how much vanadium can be reduced into iron, but whether that vanadium should remain in the

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metal or be transferred to slag in the next step (Bian et al., 2023; Guo et al., 2026; H. Liu et al., 2026; Romero et al., 2026).

1.2 Central thesis: vanadium destination engineering

This review uses the term vanadium-bearing pig iron operationally for an Fe–C-rich metallic product in which vanadium has been intentionally recovered into the metal phase, whether the product is tapped liquid or solidified after smelting. The term is distinguished from conventional pig iron containing only residual V, from vanadium-bearing hot metal produced explicitly for converter extraction, and from ferrovanadium, which is a much more concentrated Fe–V alloy used for precise alloy additions. No universal V threshold is imposed because the useful V concentration depends on the intended downstream application.

The central thesis is that vanadium is not intrinsically an impurity or a product while it resides in Fe–C metal. Its status depends on destination. For converter extraction, a high and readily oxidizable V inventory is useful. For gray, ductile, or wear-resistant cast iron, vanadium can be deliberately retained because VC precipitation and microstructural refinement can be beneficial. For direct steel alloying, the usefulness of Fe–C–V depends on the accompanying C, Si, S, P, Ti, Cr, and Mn loads and on the precision required in final chemistry (Cao et al., 2023; He et al., 2024; Kim et al., 2021; Mao et al., 2025).

Vanadium destination engineering is not simply a relabeling of conventional flowsheet optimization. Conventional optimization normally treats the downstream product route as fixed and adjusts recovery, energy, or cost within that route. Here, the downstream destination itself becomes an upstream design variable. The same intermediate composition can therefore be judged differently depending on whether carbon, silicon, and vanadium carbides are required constituents, tolerable additions, or refining penalties. This shifts the objective from maximizing vanadium recovery into a predetermined intermediate to maximizing useful vanadium retained in a specification-compliant final product, while accounting for the conversion steps avoided or created.

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Figure 1 integrates the review logic from primary and secondary feedstocks to the final vanadium destination, highlighting the process controls that determine whether Fe–C–V should be refined, oxidized, or used directly.

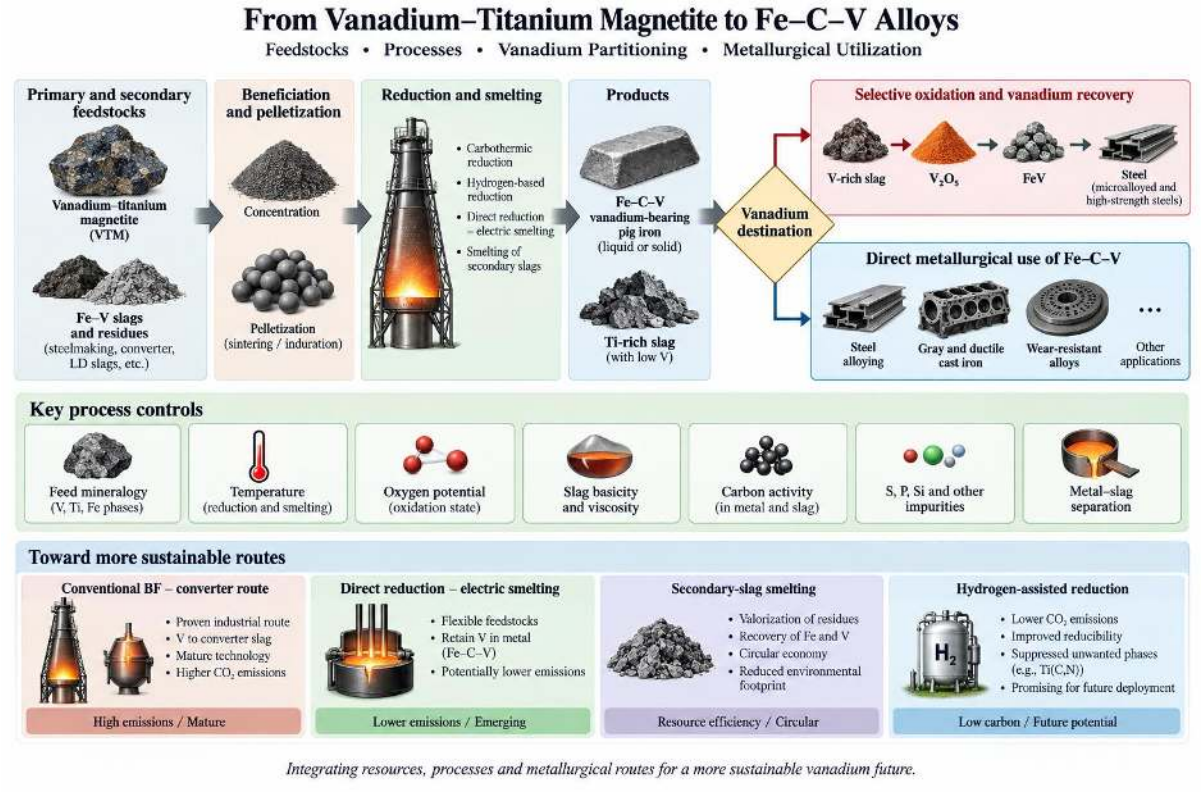

Figure 1. *Integrated pathway from vanadium-bearing feedstocks to Fe–C–V production, vanadium partitioning, and*
Note. Author-developed conceptual framework based on Gilligan and Nikoloski (2020), Wang et al. (2020), Heo et al. (2021), Romero et al. (2026), Guo et al. (2026), and H. Liu et al. (2026). This qualitative synthesis of route logic does not imply equal industrial maturity or predictive boundaries for composition.

The most important implication of Figure 1 is that the decision boundary sits after metal production, not before it. A route that achieves high V recovery to metal is not automatically superior if subsequent refining is costly or if impurities preclude direct use. Conversely, a route with a lower metal grade may be attractive when the Fe–C–V composition matches the downstream melt and avoids multiple conversion steps. The review therefore evaluates recovery, partitioning, product quality, and downstream compatibility as a coupled system rather than as isolated unit operations.

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2. Review Scope, Terminology, and Evidence Framework

2.1 Scope and literature boundaries

This is a structured critical review rather than a formal systematic review or meta-analysis. The principal analytic window covers peer-reviewed studies published from 1 January 2020 through 31 August 2026 on VTM beneficiation and agglomeration, carbothermic and gaseous reduction, hydrogen metallurgy, blast-furnace and alternative smelting, Fe–V–Ti partitioning, slag rheology, converter extraction, direct alloying, cast-iron applications, recycling, and environmental or economic assessment. Earlier sources are retained only as limited foundational anchors for durable thermodynamic, steelmaking, slag, vanadium-extraction, or cast-iron principles. The final structured search was completed on 6 September 2026, and bibliographic metadata were re-audited on 13 September 2026. The purpose is not publication counting but critical comparison of what different evidence types can legitimately establish.

A recurring problem in this field is evidence substitution. A thermodynamic equilibrium calculation can identify a feasible direction of V transfer but cannot establish industrial recovery; a laboratory crucible test can demonstrate chemical possibility but not reactor operability; a hot-metal study may establish extraction kinetics without proving the quality of a solid pig-iron product. The review therefore separates evidence by the physical object actually studied and by scale (He et al., 2023; Heo et al., 2021; Wang et al., 2020; Wright & Davidson, 2021).

Contemporary findings were interpreted against a deliberately small set of foundational references rather than allowing older literature to dominate the analytic corpus. The durable anchors cover vanadium extractive metallurgy (Gupta & Krishnamurthy, 1992), slag thermochemistry and property relations (Verein Deutscher Eisenhüttenleute, 1995), steelmaking thermodynamics and oxidation practice (Turkdogan, 1996), and cast-iron metallurgy and alloy design (Davis, 1996). These sources provide background principles only and are not counted among the 70-source contemporary analytic corpus.

2.2 Search strategy and study selection

Google Scholar was the primary discovery platform for the final corpus. Searches were organized as process-chain Boolean families rather than a single master query; publisher journal pages and

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DOI-resolvable records were then used to verify bibliographic metadata and article status. Backward and forward citation tracing from key reviews and primary studies identified directly relevant records that terminology variation might miss. Search terms covered feed mineralogy, metal production, vanadium partitioning, hydrogen reduction, downstream alloying, and system-level performance. Table 1 reports the representative Boolean query families used for the structured update. During screening, we resolved duplicates/versions using DOI first, followed by normalized title and author–year matching; we preferred a stable version of record when available.

Table 1. Representative Boolean search blocks used to construct and update the critical-review corpus

Search block	Representative Boolean string	Role in synthesis
Feed/mineralogy	("vanadium titanomagnetite" OR VTM) AND (mineralogy OR beneficiation OR pellet* OR sinter*)	Feed representativeness and preparation
Reduction/smelting	("vanadium titanomagnetite" OR VTM) AND (reduction OR smelting OR "electric furnace" OR "blast furnace") AND (vanadium OR titanium)	Fe–V–Ti reduction and metal/slag production
Fe–C–V product	("vanadium-bearing pig iron" OR "vanadium-bearing hot metal" OR "Fe-C-V") AND (production OR smelting OR partition* OR recovery)	Direct evidence for the central thesis
Partition/slag	(vanadium AND slag AND iron) AND (partition* OR distribution) AND (FeO OR TiO2 OR basicity OR "oxygen potential" OR viscosity)	Chemical partitioning and physical separation
Hydrogen routes	("vanadium titanomagnetite" OR VTM) AND (hydrogen OR H2) AND (reduction OR "shaft furnace" OR smelting)	Low-carbon reduction and integration
Downstream use	(vanadium OR "Fe-C-V") AND ("direct alloying" OR steelmaking OR "gray cast iron" OR "ductile iron" OR "wear-resistant")	Application-adjusted quality
System performance	("vanadium titanomagnetite" OR "vanadium slag") AND ("life cycle" OR "techno-economic" OR carbon OR scale-up OR industrial)	TEA/LCA and scale-up evidence

Note. Search strings represent query families rather than an exhaustive systematic search. We used variants in spelling, hyphenation, chemical notation, and terminology during iterative retrieval. For the structured update, we screened relevance-ranked results within each query family and used citation chaining to test coverage.

Studies were included when they provided at least one of the following: direct Fe–C–V or vanadium-bearing hot-metal production data; quantified metal/slag partitioning; mechanistic reduction or slag-rheology evidence directly transferable to VTM; industrial or scale-relevant reactor evidence; downstream alloy-performance evidence relevant to a plausible Fe–C–V

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destination; or route-level environmental/economic analysis. Duplicate reports, records lacking traceable metallurgical evidence for the claim being made, and studies whose vanadium context could not be connected to the review decision space were excluded. Screening proceeded from title/abstract relevance to article-level eligibility. Historical gross retrieval and intermediate exclusion counts were not prospectively retained; they were therefore not reconstructed retrospectively as PRISMA-style counts. The analytic corpus contains 70 contemporary sources; four pre-2020 foundational anchors are cited outside that analytic count. Supplementary Table S1 provides the source-level evidence matrix, and Supplementary Table S2 documents the narrative source-selection flow and the status of retained counts.

2.3 Terminology and two-axis evidence framework

Table 2 separates two questions that should not be conflated: how directly a study addresses the Fe–C–V thesis (relevance Levels I–V) and how far the demonstrated route has progressed toward integrated operation (maturity M1–M6). The tags are author-developed interpretive classifications used for transparent synthesis; they are not statistical weights, quality scores, or validated predictors. A single reviewer-author performed the classification, and it was not independently recoded; accordingly, we do not report an inter-rater statistic. We present the source-level assignments in Supplementary Table S1 so readers can audit or challenge individual judgments. Relevance and maturity are orthogonal: a highly relevant laboratory study can remain low in maturity, whereas routine industrial evidence can address only an adjacent part of the direct-use thesis.

Table 2. Operational terminology and two-axis evidence framework used in this critical review

Item	Operational definition	Interpretive role
Conventional pig iron	Fe–C metal in which V is residual or not intentionally targeted	Context only
V-bearing hot metal	Liquid iron produced with V intentionally retained before a later extraction or steelmaking step	Direct evidence for metal chemistry and converter behavior
V-bearing pig iron / Fe–C–V	Liquid or solid Fe–C product in which V is deliberately recovered to the metal phase and characterized	Highest relevance for direct-use arguments
Ferrovanadium (FeV)	Concentrated Fe–V master alloy for controlled V addition	Benchmark downstream product
Relevance Level I	Direct production and characterization of Fe–C–V / V-bearing pig iron	Strongest evidence for the central thesis

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Relevance Level II	Production and processing of V-bearing hot metal	Strong for partitioning and extraction
Relevance Level III	Reduction–smelting of VTM with metal/slag analyses	Strong mechanistic evidence
Relevance Level IV	Fe–V alloy recovery from slags and residues	Strong for circular routes
Relevance Level V	Use of V in steels or cast irons without producing the Fe–C–V intermediate	Supports application compatibility, not production feasibility
Maturity M1	Foundational thermodynamic/model study, short screening test, or adjacent application evidence without integrated reactor demonstration	Supports direction, feasibility screening, or application compatibility only
Maturity M2	Bench/laboratory reactor or smelting study with quantified operating conditions and metal/slag or product data	Establishes mechanism or process possibility under controlled conditions
Maturity M3	Pilot batch or integrated batch-scale campaign linking multiple process steps with material-balance evidence	Demonstrates scale-relevant integration but not sustained continuous operation
Maturity M4	Continuous pilot campaign with representative feed, stable tapping/operation, and closed material/energy accounting	Strong evidence of continuous operability below industrial production scale
Maturity M5	Industrial demonstration campaign with production-scale equipment and integrated upstream/downstream operation	Strong evidence of industrial demonstrability, but not yet routine commercial practice
Maturity M6	Routine commercial operation with sustained production, representative feed variability, process control, and qualified products	Highest maturity: established commercial operability and product acceptance

Note. Author-developed interpretive framework based on terminology and process distinctions used in recent VTM, hot-metal, pig-iron, and slag-recycling literature (Bian et al., 2023; Gilligan & Nikoloski, 2020; Lee et al., 2021; Romero et al., 2026; Wang et al., 2024). Relevance and maturity are orthogonal. The classifications are qualitative synthesis tags, not independently validated scoring instruments.

Table 2 prevents two common overclaims. First, vanadium improving a cast iron does not prove that a particular V-bearing pig iron can be used directly; the intermediate must also meet impurity, dissolution, mass-balance, and process-control requirements. Second, laboratory direct-production evidence should not be equated with industrial readiness. Conversely, evidence that V can be efficiently oxidized from hot metal does not imply that oxidation is always the value-maximizing destination.

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2.4 Critical endpoints

Four endpoints are used repeatedly. First, metallurgical recovery measures how much V enters the metallic phase. Second, partitioning describes how V is distributed between metal and slag at a given operating condition. Third, application-adjusted quality is defined here as the suitability of an Fe–C–V product for a specified downstream destination after accounting for useful elements, impurity penalties, required composition correction or refining, dissolution behavior, and final-property requirements. Fourth, life-cycle vanadium utilization measures the fraction of feed V that ultimately remains in a useful final product. A second distinction is applied from the outset when interpreting slag assays: vanadium reporting to slag may be a chemical loss as oxidized V species or a physical loss carried by entrained Fe–C–V droplets. These loss modes require different remedies and must not be inferred from total slag V alone. Together, these endpoints deliberately separate first-stage success from whole-chain value.

$$R_v,\text{metal} = 100 \times m_v,\text{metal} / m_v,\text{feed} \quad (1)$$

$$L_v = w_v,\text{metal} / w_v,\text{slag} \ \text{(distribution convention used in this review)} \quad (2)$$

$$\eta_v,\text{use} = \text{V retained in useful final product / V in original feed} \quad (3)$$

3. Vanadium-Bearing Feedstocks, Process Mineralogy, and Feed Preparation

3.1 VTM as a coupled Fe–Ti–V resource

VTM is not a simple magnetite containing a freely separable vanadium mineral. Vanadium commonly occurs by isomorphous substitution within magnetite/titanomagnetite and related spinel structures, whereas titanium is associated with titanomagnetite, ilmenite, exsolution textures, and secondary Ti-bearing phases. Consequently, the liberation scale that improves magnetic recovery of iron may not fully liberate V from the Fe-bearing phase, and aggressive comminution can increase energy demand without creating a separate V concentrate (Fang, Dang, et al., 2026; van Gerve et al., 2026; Yu et al., 2020; Zhu et al., 2023).

Process mineralogy is therefore a scale-up variable, not only a characterization step. The abundance and size of exsolution lamellae, iron oxidation state, degree of weathering, and distribution of Si-, Al-, Mg-, Ca-, Cr-, and P-bearing gangue determine both beneficiation response and later slag chemistry. Recent beneficiation studies show that grinding intensity and magnetic separation can improve Fe/V concentration, but the achievable selectivity depends strongly on the

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textural association of magnetite, ilmenite, and gangue (Guo et al., 2020; Li et al., 2020; Liu et al., 2022; Sadangi et al., 2026).

3.2 Primary versus secondary feeds

Primary feeds include run-of-mine VTM, concentrates, pellets, and sinter. Secondary feeds include converter vanadium slag, V-bearing steel slags, Waelz and fayalitic slags, dusts, and other Fe–V residues. The distinction matters because a primary VTM route must reject or recover large Ti inventories, whereas a secondary-feed route may be dominated by impurity control, slag self-fluxing, zinc volatilization, or the recovery of Fe and V from an already oxidized matrix (Lee et al., 2021; Petranikova et al., 2020; Romero et al., 2026; Yang & Yang, 2024).

A particularly important 2026 demonstration combined Linz–Donawitz, Waelz, and fayalitic slags to create a self-fluxing mixture. Scale-up smelting of the optimized mixture produced a metal containing 86.53 wt% Fe, 1.65 wt% C, and 1.81 wt% V, with approximately 91% V recovery to the metal. The same product also contained 6.39 wt% Si and 0.44 wt% S, illustrating the central trade-off of secondary routes: high V recovery can coexist with a refining burden that determines whether direct alloy use is realistic (Romero et al., 2026).

3.3 Feed preparation as a metallurgical control

Crushing, grinding, magnetic separation, pelletizing, sintering, briquetting, pre-oxidation, and pre-reduction change more than feed size. They influence reducibility, permeability, reduction disintegration, diffusion length, liquid formation, and the spatial distribution of Ti- and V-bearing phases. Therefore, evaluate pellet and sinter design against the chosen reactor rather than against green or fired strength alone (Li et al., 2021; Lv et al., 2024; Yang et al., 2021).

Table 3 summarizes the major feed classes and the process-mineralogical attributes that directly affect the Fe–C–V route.

Table 3. *Feed classes and process-mineralogical implications for vanadium-bearing Fe–C–V production*

Feed class	Typical mineralogical/chemical feature	Critical process implication	Relevant route
VTM concentrate	V mainly in magnetite/titanomagnetite; Ti in	Liberation, Fe/V recovery, Ti rejection, pellet quality	BF, DR–electric smelting, H_2-assisted routes

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	titanomagnetite/ilmenite; variable gangue		
Low-grade/refractory VTM	Fine intergrowths, weathering/alteration, lower magnetic selectivity	Grinding energy, magnetic separation selectivity, gangue load	Beneficiation + agglomeration before smelting
VTM pellets/sinter	Engineered porosity and bonding phases	Strength, reduction disintegration, swelling, reducibility, softening–melting	BF or shaft/direct reduction
Converter/steelmaking V slag	Oxidized V in complex Fe–V–Cr–Ti phases	Reduction selectivity, Fe recovery, Cr/Ti behavior	Smelting reduction or hydrometallurgical recovery
Mixed industrial slags	Heterogeneous Fe, V, Zn, Si, Ca, Mg, S and minor metals	Self-fluxing window, volatility, impurity transfer, metal coalescence	Circular smelting to Fe–C–V + cleaned slag

Note. Author-developed evidence summary based on Guo et al. (2020), Liu et al. (2022), Fang, Dang, et al. (2026), van Gerve et al. (2026), Zhu et al. (2023), and Romero et al. (2026).

Table 3 shows why feed composition cannot be reduced to total Fe, V_2O_5, and TiO_2. Two feeds with the same bulk V grade may show very different reduction and separation behavior if V is hosted in different spinels or if Ti-rich exsolution textures change liberation and the liquid-slag sequence. For scale-up, a representative feed specification should therefore include mineralogical texture, PSD, gangue chemistry, oxidation state, and agglomerate properties.

4. Production Routes for Vanadium-Bearing Pig Iron and Fe–C–V Metal

4.1 Blast-furnace route

The blast furnace remains the reference industrial route for large-scale VTM ironmaking. Its principal advantages are throughput, thermal integration, and established operation with vanadium-bearing burdens. Its main VTM-specific challenge is the titanium-bearing slag system: Ti-rich phases, Ti(C,N) formation under strongly reducing, carbon-rich conditions, and changing slag viscosity can affect permeability, hearth drainage, refractory interaction, and metal–slag separation. Vanadium generally reports preferentially to the hot metal under reducing ironmaking conditions, after which converter oxidation is used to concentrate V in slag (Gao et al., 2022; He et al., 2023; Zhang, Wang, et al., 2022; Zhang et al., 2026).

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4.2 Direct reduction followed by electric smelting

Separating solid-state reduction from melting creates a more flexible route. Metalized pellets can be produced with coal, CO-rich gas, hydrogen-rich gas, or hydrogen, then smelted in an electric furnace to separate Fe–C–V metal from a Ti-rich slag. This decoupling permits tighter control of metallization and slag chemistry and offers a pathway to lower direct fossil-carbon consumption, although electric energy demand and downstream slag treatment remain important (Guo et al., 2025; Guo et al., 2026; Vickerfält et al., 2021).

Recent laboratory work obtained a vanadium-bearing metallic product containing 92.07 wt% Fe and 1.27 wt% V by smelting metalized VTM pellets at 1690 °C for 20 min with 2.5 wt% coke. The accompanying slag contained 47.83 wt% TiO_2, and higher slag basicity improved V transfer to the metal but reduced the TiO_2 grade available for subsequent upgrading. This is an instructive example of a multi-product trade-off: conditions maximizing V recovery do not necessarily maximize the value of the Ti-rich slag (Guo et al., 2026).

4.3 Sodium-assisted and lower-temperature smelting

Sodium-assisted smelting has been explored to modify VTM phase chemistry, lower the temperature required for metallization and smelting, and control impurities in the resulting V-bearing pig iron. Experimental studies show that sodium addition, reductant dosage, temperature, and holding time strongly affect titanium impurities, while V-rich carbide phases may precipitate during metal cooling (Bian et al., 2023; Cao et al., 2023).

4.4 Smelting reduction of secondary resources

Smelting reduction of V-bearing slags or mixed residues offers a circular economy route, recovering iron and vanadium as separable metals. Residual slag can be upgraded or used in construction or ceramics. The process is beneficial when feed blending creates favorable basicity without major flux addition and volatile elements like Zn are recoverable. Constraints include compositional variability, sulfur and silicon transfer, metal-droplet coalescence, and ensuring slag meets end-use specs (Lee et al., 2021; Petranikova et al., 2020; Romero et al., 2026).

Figure 2 compares the principal production routes and makes explicit that the same Fe–C–V intermediate can feed three fundamentally different downstream destinations.

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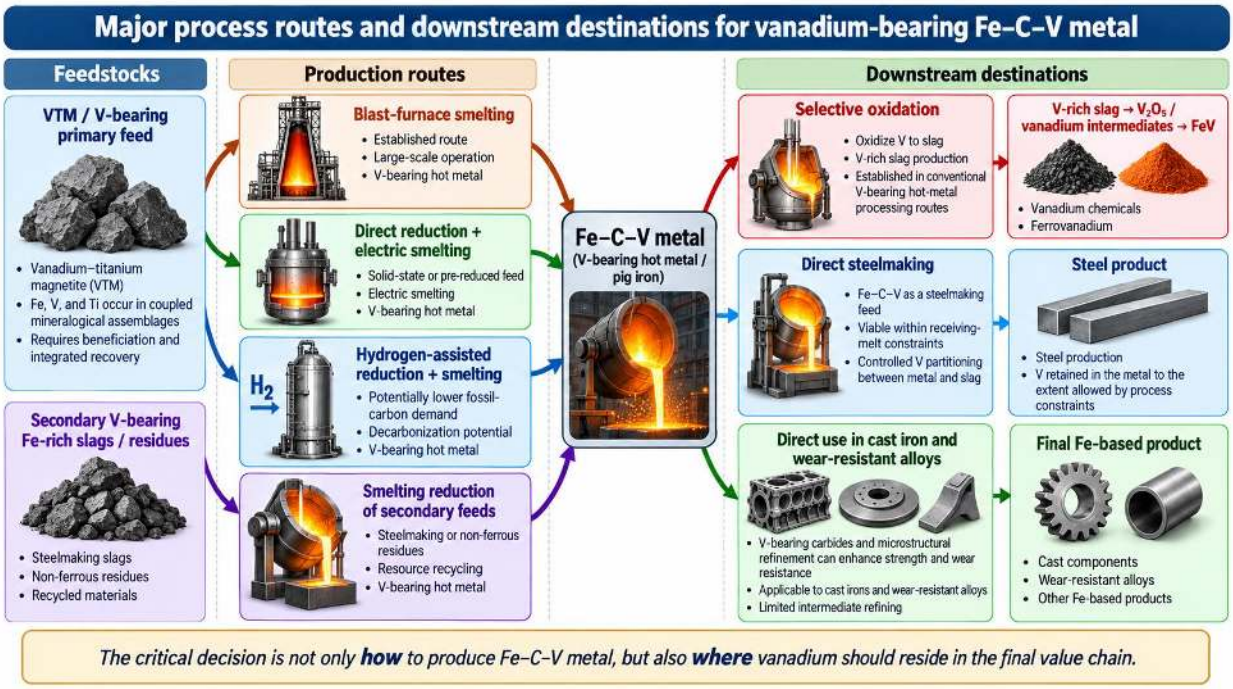

Figure 2. *Major process routes and downstream destinations for vanadium-bearing Fe–C–V metal*

Note. Author-developed route-comparison evidence summary based on recent blast-furnace, direct-reduction/electric-smelting, hydrogen, and secondary-slag studies (Gao et al., 2022; Guo et al., 2026; H. Liu et al., 2026; Romero et al., 2026).

Figure 2 emphasizes that route comparison must extend beyond the smelter. A process that creates a higher-V metal may still require converter extraction, while a lower-V product with acceptable C, Si, S, and P could be used more directly. The decision should therefore be based on total processing burden and final-product compatibility.

Because route maturity is often described qualitatively, Table 4 extracts the most decision-relevant quantitative and scale-relevant evidence from studies that directly produce V-bearing metal or test a downstream vanadium destination. Do not compare the values as if they were generated under a common feed basis; they are meant to expose the evidence density, scale, and composition constraints behind the route claims.

Table 4. Representative quantitative and scale-relevant evidence for Fe–C–V production and downstream use

Study / route	Feed, reactor, scale	Key conditions	Metal product / quality	V–Ti outcome	Relevance / maturity
Wang et al. (2020).	VTM metallized pellets; laboratory smelting	CaO, MgO, and	V in pig iron increased with	V recovery increased; slag/metal V ratio	Level III; M2

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		temperature varied	optical basicity and temperature	decreased; Mg-bearing anosovite favored	
Bian et al. (2023)	VTM sodium smelting; 100 g laboratory charges; route has 50,000 t/y pilot background cited by authors	≈1200 °C; ≥2 h; Na_2CO_3 ≥60%; anthracite ≈25–35%	Optimized V-bearing pig iron with Ti controlled to ≈20 ppm; full V grade not the study endpoint	Low-temperature smelting and Ti-impurity control broaden direct-use potential	Level I; M2 study / M3 route context
Romero et al. (2026)	41 wt% LD + 10 wt% Waelz + 48 wt% fayalitic slag; 2 kg induction scale-up	≈1450 °C; self-fluxing basicity ≈0.9–1.0	Fe 86.53, C 1.65, V 1.81, Si 6.39, S 0.44 wt%	V recovery ≈91%; residual slag qualified as non-hazardous construction material	Level I/IV; M2 scale-relevant
Guo et al. (2026)	Metallized VTM pellets; laboratory induction-furnace smelting	1690 °C; 20 min; 2.5 wt% coke	Fe 92.07 wt%; V 1.27 wt%	Initial slag 47.83 wt% TiO_2; downstream Ti product 90.70 wt% TiO_2 with 88.75% Ti recovery	Level I/III; M2
H. Liu et al. (2026)	40% VTM + 50% high-grade iron ore + 10% Ti concentrate; industrial H_2 shaft + electric smelting	H_2 reduction 800–1000 °C; kiloton-scale shaft trial	V-bearing hot metal; complete composition not reported in the review summary	Fe, V and Ti recoveries >90%; Ti-rich slag ≈45 wt% TiO_2	Level II/III; M5 industrial demonstration
Xin et al. (2021, 2022)	Self-reducing V-slag briquettes added directly to molten steel; laboratory	Optimized self-reduction / alloying conditions	Not a Fe–C–V pig-iron product	V recovery to steel approached 90%	Level V; M2; application evidence only

Note. Values are reported by the cited studies and are not normalized across feed bases or reactor configurations. Maturity grades follow Table 2. 'Route context' distinguishes a laboratory paper from the larger pilot infrastructure cited by that paper.

Table 4 makes the central evidence limitation explicit. Strong laboratory and scale-relevant demonstrations exist, but very few studies combine a deliberately produced Fe–C–V composition, a complete impurity inventory, continuous operation, and validated downstream melt performance. Consequently, frame direct-use claims as destination-specific hypotheses supported by uneven evidence rather than as established universal practice.

Table 5 compares major production routes by maturity, process-control leverage, and critical limitations.

Table 5. *Comparison of major Fe–C–V production routes*

Route	Current maturity	Main advantage	Primary constraint	Typical product logic

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Received: 17/08/2026 - **Accepted:** 17/09/2026
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BF VTM smelting	M6: routine commercial operation	High throughput; integrated heat and carbon	Ti-bearing slag, coke/carbon intensity, complex hearth chemistry	V-bearing hot metal → converter extraction
DR + electric smelting	M3–M5: pilot/integrated to industrial demonstration, route dependent	Decoupled reduction/smelting; flexible reductant; Ti-rich slag potential	Electricity demand; DRI quality; slag design	Fe–C–V metal, Ti-rich slag
H_2-assisted DR + electric smelting	M5 at demonstration level for integrated shaft reduction + smelting; not routine commercial VTM operation	Lower direct carbon demand; high metallization potential	Pellet reducibility/disintegration; electricity/H_2 supply; microstructure	Fe–V hot metal + Ti-rich slag
Sodium-assisted smelting	M2–M3: laboratory evidence with pilot route context	Lower-temperature chemistry; impurity control potential	Na balance, refractory/corrosion, slag recycle, product consistency	V-bearing pig iron
Secondary-slag smelting	M2–M3: bench/scale-up batch evidence	Circular Fe/V recovery; potential self-fluxing feeds	Feed variability, S/Si, Zn/volatile handling, slag qualification	Complex Fe–C–V alloy + cleaned slag

Note. Author-developed route-maturity evidence summary based on Gao et al. (2022), Bian et al. (2023), Guo et al. (2026), H. Liu et al. (2026), and Romero et al. (2026).

Table 5 shows that technology maturity and product strategy are not identical. The BF route is mature but normally embeds V extraction as a downstream necessity; hydrogen-assisted and secondary-smelting routes are less mature but can create new product combinations. Industrial competitiveness will depend on whether those combinations avoid enough refining, flux, coke, and residue treatment to offset new costs.

5. Thermodynamics and Reduction Mechanisms in Fe–V–Ti–C–O Systems

5.1 Sequential reduction and the meaning of "vanadium recovery"

Iron oxide reduction proceeds through the familiar hematite–magnetite–wüstite–iron sequence, while vanadium can pass through multiple oxidation states before metallic V dissolves in iron. Titanium oxides are substantially harder to reduce under conditions where Fe reduction is already extensive. This relative reducibility creates the desired first-order separation: Fe and a significant fraction of V can report to the metallic phase while much of Ti remains oxidized in slag. The

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Journal International Review of Research Studies
Received: 17/08/2026 - **Accepted:** 17/09/2026
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separation is not absolute, however, because carbonitride and carbide formation, oxygen potential, and local interfacial chemistry shift the stability fields (Chen et al., 2022; Qin et al., 2020; Sun et al., 2026).

Vanadium recovery into metal should therefore not be interpreted as a single reduction reaction. It includes V release from spinel structures, progressive oxygen removal, diffusion through the reduced matrix, dissolution into metallic Fe, and possible precipitation as V-rich carbides during cooling. Each step can become rate-limiting depending on temperature, reductant, pellet microstructure, and the time at which melting begins (Ji et al., 2026; Shi et al., 2024; Shu et al., 2026).

5.2 Carbon: reductant, carburizer, and phase-control variable

Carbon has three simultaneous functions. It supplies reducing potential, controls CO/CO_2 equilibria, and carburizes iron, lowering its liquidus and facilitating early metal melting. Yet high carbon activity also promotes carbide and carbonitride formation, including VC, $(Fe,V)_3C$-derived phases, TiC, and Ti(C,N). These phases may be helpful or harmful depending on destination. V carbides can strengthen wear-resistant alloys, whereas Ti(C,N) can complicate blast-furnace operation and metal quality (Cao et al., 2023; Zhang et al., 2026).

$$C + CO_2 \rightleftharpoons 2CO \quad (4)$$

$$MO + CO \rightleftharpoons M + CO_2 \quad (5)$$

5.3 Solid-state reduction, morphology, and later separation

Reduction kinetics alone do not predict smelting performance. Hydrogen can achieve fast oxygen removal and high metallization, but the morphology of the metallic iron domains controls subsequent coalescence and liberation from Ti-bearing and gangue phases. Recent work comparing H_2 and CO reduction showed that H_2 can promote dense nucleation of fine iron domains and high metallization while creating an ‘iron-cage’ microstructure that may hinder later Fe/Ti liberation. This finding is important because a process can be chemically faster while becoming physically harder to separate (Shu et al., 2026).

Other hydrogen and hydrogen-rich studies similarly show that pre-oxidation, gas composition, temperature, and reduction degree change pore development, phase migration, and reduction

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Journal International Review of Research Studies
Received: 17/08/2026 - **Accepted:** 17/09/2026
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disintegration. The practical design variable is therefore not maximum metallization alone but the combination of metallization, pellet integrity, metallic-domain coarsening, and the smelting behavior of the resulting DRI (Chen et al., 2025; He et al., 2026; Hu et al., 2023; Ji et al., 2026; Shi et al., 2024; Shi et al., 2025; Yu et al., 2022).

5.4 Coupled thermodynamic–kinetic interpretation

A useful critical distinction is between thermodynamic selectivity and process selectivity. Thermodynamic selectivity describes which phase is favored at equilibrium; process selectivity describes what the reactor actually achieves within finite residence time, finite interfacial area, heterogeneous temperature, and changing slag chemistry. For VTM, the latter is often decisive. A thermodynamically favorable V-to-metal direction can be offset by insufficient mass transfer or by physical entrainment of metal droplets in slag; similarly, a high reduction degree can still yield poor separation if metallic domains do not coalesce.

6. Vanadium Partitioning, Slag Engineering, and Metal–Slag Separation

6.1 Partitioning is a coupled chemical and physical problem

Vanadium distribution between molten iron and slag is governed primarily by oxygen potential, slag composition, temperature, and the activity of V in the metal. Under more reducing conditions, V oxide reduction and dissolution into Fe–C metal are favored. Under more oxidizing conditions, V transfers to the slag. Experimental VTM smelting has shown that increasing CaO, MgO, and temperature can increase V recovery to pig iron while decreasing the slag/metal distribution ratio under the convention used by those authors (Wang et al., 2020).

Slag chemistry changes partitioning through more than a single ‘basicity’ number. FeO directly changes oxygen potential and also modifies slag structure and viscosity; TiO_2 influences liquidus and phase formation; Al_2O_3 and SiO_2 control network polymerization; MgO and CaO affect both basicity and crystalline phase stability. In FeO–TiO_2–MgO–SiO_2–Al_2O_3 slags, measured V distribution responds to FeO/TiO_2 ratio, $Al_2O_3/(SiO_2+Al_2O_3)$, and pO_2, showing why basicity alone is an incomplete scale-up descriptor (Heo et al., 2021; Wright & Davidson, 2021).

Figure 3 presents a qualitative map of the chemical control direction and explicitly separates it from the physical separation problem.

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Journal International Review of Research Studies
Received: 17/08/2026 - **Accepted:** 17/09/2026
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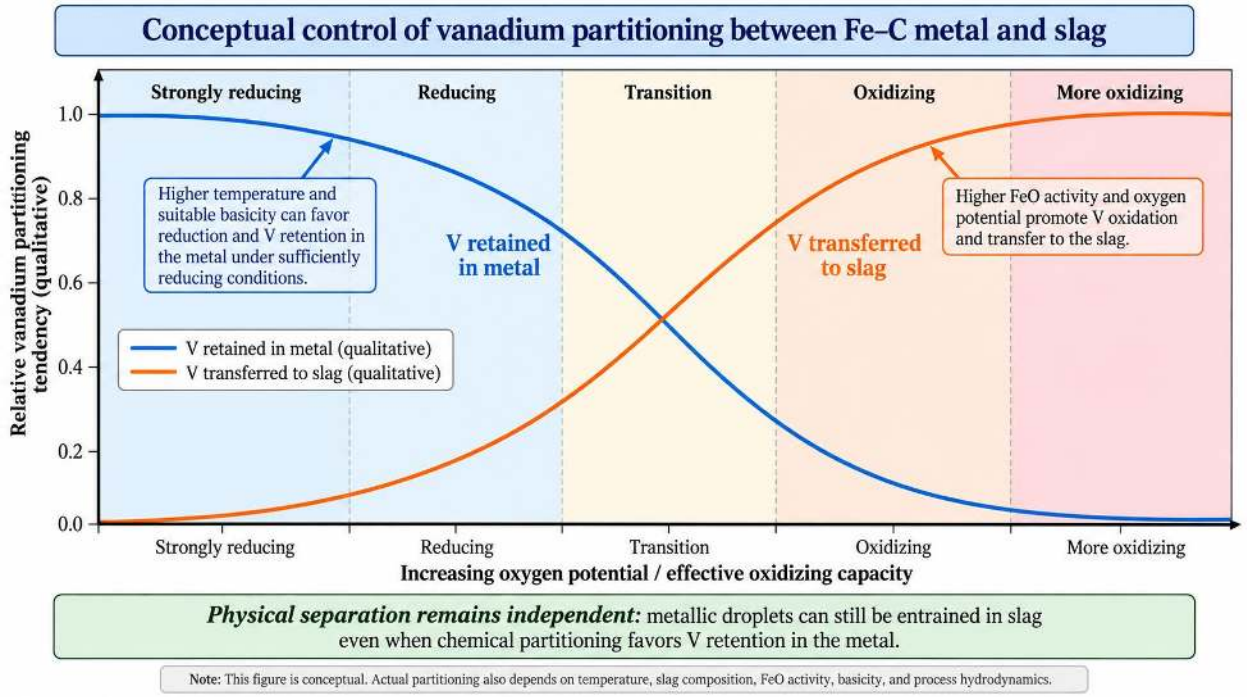

Figure 3. *Conceptual control of vanadium partitioning between Fe–C metal and slag*

Note. Author-developed qualitative directional map based on Wang et al. (2020), Heo et al. (2021), Wright and Davidson (2021), and Zhou et al. (2026). Curves are conceptual, not fitted to experimental data, and must not be interpreted as quantitative equilibrium boundaries.

Figure 3 should not be used as a quantitative equilibrium diagram. Its purpose is to emphasize directionality: increasing oxidizing capacity shifts V toward slag, while strongly reducing smelting favors metal retention. The actual transition window depends on slag chemistry, metal carbon activity, temperature, and residence time, and must be established for each feed–reactor system.

6.2 Slag viscosity, liquidus, and Ti-rich phase evolution

High-TiO_2 slags are particularly sensitive to phase constitution. Their apparent fluidity may change sharply near the precipitation temperature of pseudobrookite-type or other Ti-rich phases, producing ‘short-slag’ behavior in which viscosity rises rapidly over a narrow temperature interval. This matters for tapping, droplet settling, refractory exposure, and the time available for V exchange at the interface (Ma et al., 2025; Zhang et al., 2024; Zhou et al., 2026).

Recent slag-optimization work for V–Ti magnetite smelting identified a compositional window that maintains low liquidus temperature, manageable viscosity, high V recovery, and good slag–iron separation. The central lesson is not the universality of one composition window but the need

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Journal International Review of Research Studies
Received: 17/08/2026 - **Accepted:** 17/09/2026
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DOI: 10.66104/qa1tk476
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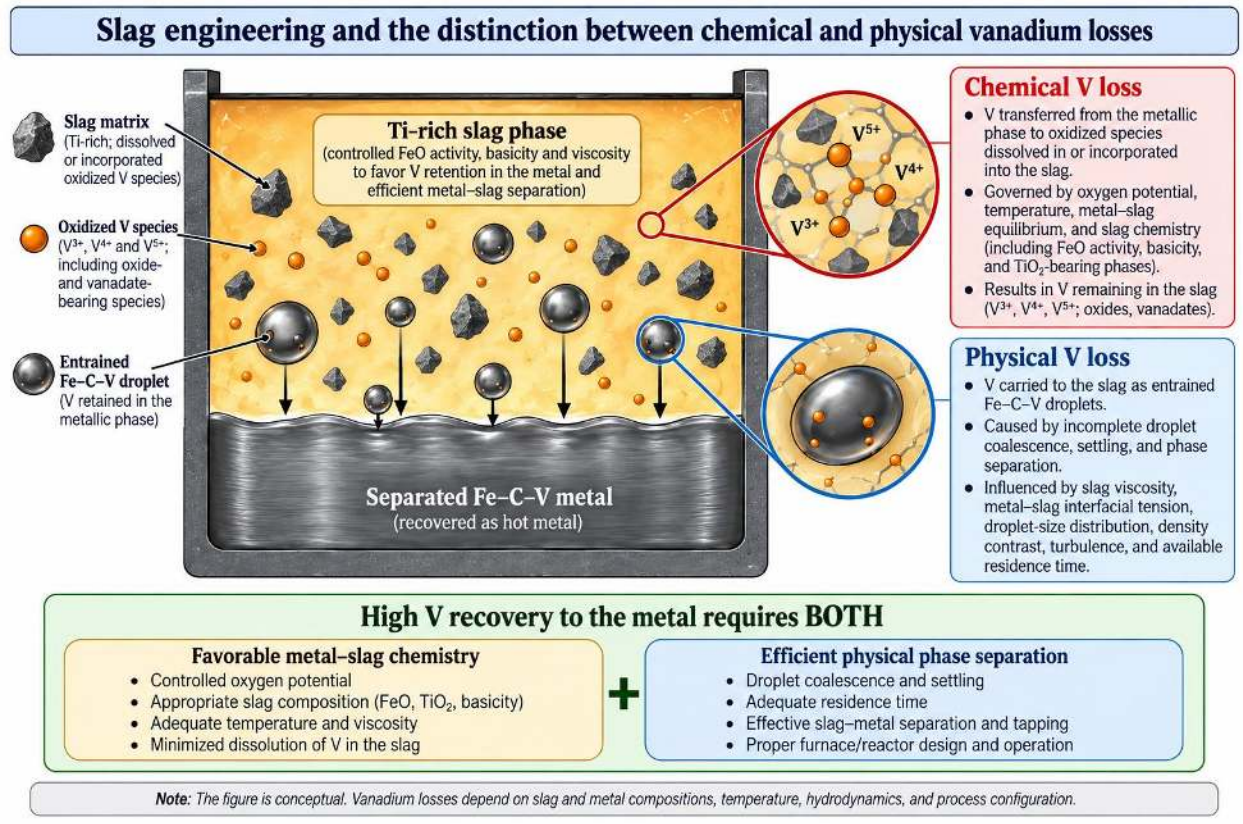
to optimize phase stability, chemistry, and separation simultaneously. A slag that is chemically favorable for V reduction but too viscous for droplet settling can still generate poor overall metal recovery (Zheng et al., 2026).

6.3 Chemical versus physical vanadium loss

Vanadium in final slag can have two fundamentally different origins. Chemical loss is V that remains as oxidized slag species because the equilibrium or reaction path did not reduce it into metal. Physical loss is V carried by entrained Fe–C–V droplets that failed to coalesce, settle, or separate before tapping. These loss modes require different remedies: stronger reduction or modified oxygen potential for chemical loss, and improved viscosity, interfacial conditions, mixing, residence time, droplet coalescence, and settling for physical loss (He et al., 2020; Lai et al., 2026; Zheng et al., 2026).

Figure 4 illustrates this distinction, which is frequently obscured when only total V in slag is reported.



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Received: 17/08/2026 - **Accepted:** 17/09/2026
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Figure 4. *Slag engineering and the distinction between chemical and physical vanadium losses*
Note. Author-developed evidence summary based on studies of iron-droplet coalescence, settling, slag rheology, and V–Ti slag–metal separation (He et al., 2020; Lai et al., 2026; Zheng et al., 2026). The graphic distinguishes mechanisms qualitatively rather than assigning measured loss fractions.

Figure 4 implies that a complete scale-up mass balance should quantify total metallic entrainment in slag, not only dissolved or oxidized V. Otherwise, a reactor may appear thermodynamically inefficient when the dominant problem is hydrodynamic. Conversely, a cleanly separated slag can still contain excessive chemically oxidized V if oxygen potential is too high.

$$V_{slag,total} = V_{oxidized\ in\ slag} + V_{in\ entrained\ Fe–C–V\ droplets} \quad (6)$$

A practical separation protocol should therefore pair bulk slag chemistry with direct evidence of entrained metallic phases, such as polished-section metallography/SEM–EDS, magnetic- or density-based separation of metallic inclusions, XCT or three-dimensional image analysis, and droplet-size or metal-yield mass balances. Without this distinction, a high total V assay in slag can be misattributed to chemical-partitioning failure when hydrodynamic entrainment dominates (He et al., 2020; Lai et al., 2026; Zheng et al., 2026).

Table 6 consolidates the main control variables and the failure mechanisms they influence.

Table 6. *Variables controlling vanadium partitioning and metal–slag separation*

Variable	Primary effect	Representative failure mode	Scale-up measurement
Oxygen potential / FeO	Higher oxidizing capacity transfers V from metal to slag	V over-oxidation during smelting; intentional V extraction during refining	FeO, metal V, slag V, off-gas/redox indicators
Temperature	Changes equilibrium, liquidus, viscosity, kinetics and droplet settling	Low-T solidification/short slag; excessive refractory/energy load	Bath and slag temperature; thermal gradients
Basicity (CaO, MgO)	Changes V reduction behavior, phase stability and slag structure	Over-fluxing can dilute Ti product or alter liquidus	CaO/SiO_2, optical basicity, MgO
TiO_2	Controls Ti-rich phases and slag rheology	High viscosity, pseudobrookite precipitation, Ti transfer	TiO_2, phase analysis, viscosity/free-running temperature
Carbon activity	Drives reduction and carburization; affects carbide formation	Excess C, VC/TiC/Ti(C,N), downstream refining load	Metal C, fixed-C feed, gas composition

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Received: 17/08/2026 - **Accepted:** 17/09/2026
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Mixing and residence time	Controls interfacial mass transfer and droplet collisions	Incomplete partitioning or excessive reoxidation	Power/stirring, hold time, droplet-size distribution
S/P/Si and other impurities	Determine direct-use quality and refining burden	High S/P blocks direct use; Si can be useful or harmful by destination	Metal chemistry and application specification

Note. Author-developed variable-control evidence summary based on Wang et al. (2020), Heo et al. (2021), Åström et al. (2025), Zheng et al. (2026), and Zhou et al. (2026).

Table 6 highlights the principal scale-up requirement: variables must be measured as a coupled operating window. Reporting furnace temperature without FeO, slag composition, metal carbon, and hold time prevents results from transferring across scales because the same nominal temperature can correspond to different oxygen potentials, liquid fractions, and mass-transfer regimes.

7. Reactor Engineering, Operating Windows, and Process Control

7.1 Reactor choice changes the meaning of scale-up

Blast furnaces, submerged-arc furnaces, electric arc furnaces, DC furnaces, induction furnaces, HIsmelt-type reactors, and two-stage reduction–smelting configurations impose different heat-transfer, mixing, gas–solid contact, residence-time, and slag–metal separation regimes. Geometric scale-up is therefore insufficient. The relevant similarity conditions include feed permeability, power density, reduction degree entering the smelter, bath temperature, slag liquid fraction, specific interfacial area, droplet settling time, and tapping practice (Han et al., 2025; Zhang, Hu, et al., 2022; Zhang, Wang, et al., 2022).

HIsmelt-related studies illustrate this point. Smelting time changes V and Ti distribution as the bath approaches a coupled chemical and phase equilibrium, while TiO_2 and FeO alter both viscosity and slag structure. A laboratory holding time cannot be transferred directly to an industrial vessel without considering mixing intensity, droplet size, and the distance over which droplets must settle (Ma et al., 2025; Zhang, Hu, et al., 2022; Zhang et al., 2024).

7.2 Operating window rather than single-variable optimization

An industrially useful operating window must satisfy at least five conditions simultaneously: sufficient Fe metallization and V reduction; acceptable Ti rejection from metal; slag liquidus and viscosity compatible with tapping; limited refractory and energy penalties; and a product chemistry

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Received: 17/08/2026 - **Accepted:** 17/09/2026
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compatible with the selected V destination. This multi-objective constraint explains why nominally beneficial changes can reverse at scale. For example, adding FeO can improve fluidity but also increase oxygen potential and oxidize V; increasing basicity can improve V reduction but may dilute the Ti-rich slag or shift its phase assemblage (Guo et al., 2026; Zhou et al., 2026).

7.3 Process control and observability

Modern process control should target state variables rather than operator settings alone. Furnace power, reductant addition, oxygen or gas flow, and flux dosage are manipulated variables; metal V and C, slag FeO and TiO_2, viscosity state, metal temperature, and droplet separation are the performance states. Predictive models of hot-metal V content and converter extraction show the value of combining process data with metallurgical constraints, but transferability depends on maintaining physically meaningful inputs and recalibration across ore blends (Li et al., 2023).

Scale-up should therefore include an observability plan: which variables are measured online, which are sampled intermittently, and which are inferred. Without that plan, an apparent reproduction of laboratory recovery at industrial scale may be unstable because the hidden state—especially slag oxidation and physical metal entrainment—can drift while the final metal assay remains temporarily acceptable.

8. Hydrogen-Assisted and Low-Carbon Pathways

8.1 Why hydrogen is attractive

Hydrogen-based reduction can separate oxygen removal from the carbon supply required for carburization and melting. For VTM, this is attractive because a high reduction degree can be achieved before electric smelting, potentially lowering direct coke consumption and allowing carbon to be added mainly to tune metal liquidus and final C. Mass- and energy-balance studies and recent laboratory investigations support the technical basis for hydrogen-rich and hydrogen-based reduction (Gao et al., 2022; Chen et al., 2025; Ji et al., 2026).

8.2 The pellet problem: reducibility is not enough

Pure VTM pellets can exhibit poor reducibility, low-temperature reduction disintegration, swelling, or phase evolution that is incompatible with shaft-furnace operation. These limitations

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Received: 17/08/2026 - **Accepted:** 17/09/2026
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are not secondary details: they determine whether a laboratory H_2-reduction result can be scaled to a moving-bed reactor. Gas composition and pre-oxidation alter reduction pathways, while physical degradation can compromise gas distribution and burden stability (He et al., 2026; Hu et al., 2023; Shi et al., 2024).

A 2026 integrated hydrogen-metallurgy study addressed this by blending VTM with high-grade iron ore and titanium concentrate. An optimized pellet blend was demonstrated in a hydrogen-based shaft furnace and followed by electric-furnace smelting, with reported recoveries of Fe, V, and Ti above 90%. This is among the strongest recent scale-relevant demonstrations because it links pellet design, industrial shaft reduction, and subsequent smelting rather than treating reduction as an isolated laboratory endpoint (H. Liu et al., 2026).

8.3 Hydrogen changes morphology and downstream separability

Hydrogen is not simply a low-carbon substitute for CO. Comparative reduction work found that H_2 promotes faster nucleation and higher metallization but can produce much finer metallic iron domains than CO. Fine, interconnected iron can trap gangue and Ti-bearing phases, potentially complicating liberation or coalescence during the next process step. Thus, the 'best' reduction atmosphere depends on the downstream melting and separation mechanism, not only on kinetic rate (Shu et al., 2026).

Complementary laboratory-scale electrode-smelting evidence also links H_2 reduction to the melt-separation problem. Mendoza et al. (2026) smelted hydrogen-reduced VTM ironsand pellets with reduction degrees of 85–93% and demonstrated separation of carburized hot metal from high-titania slag; most V was reported to metal, but a (Ti,V)C phase at metal–slag interfaces represented a competing mechanism for V recovery and droplet separation. This evidence strengthens the need to treat carburization, carbide formation, partitioning, and coalescence as one readiness problem rather than independent unit operations.

Table 7 compares conventional carbon-rich and hydrogen-assisted pathways using criteria that are directly relevant to industrialization.

Table 7. *Conventional and hydrogen-assisted VTM reduction–smelting pathways*

Criterion	Conventional/carbon-rich route	Hydrogen-assisted route

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Primary reduction agent	C/CO or mixed CO–H_2	H_2-rich or H_2; carbon added mainly for carburization/smelting as needed
Reduction rate	Mature and well characterized	Often faster at suitable temperature, but morphology differs
Pellet requirement	Established BF/DR specifications	May require tighter control of disintegration, swelling and reducibility
Metal morphology before melting	Often coarser Fe domains under CO-rich reduction	Potentially finer dense Fe nucleation; may trap gangue/Ti phases
Carbon intensity	High direct fossil-carbon burden in conventional BF	Potentially lower direct CO_2 if H_2 and electricity are low-carbon
Scale evidence	Mature industrial ironmaking	Emerging; includes industrial shaft-furnace demonstrations
Critical uncertainty	Ti-rich slag operability and carbon emissions	H_2 supply, electricity, pellet design, integration with smelting

Note. Author-developed pathway evidence summary based on Gao et al. (2022), Chen et al. (2025), Shu et al. (2026), and H. Liu et al. (2026).

Table 7 shows that hydrogen readiness must be assessed at the flowsheet level. A reduction reactor can be technically successful while the overall route remains unattractive if pellet preparation, electricity consumption, hydrogen production, or Ti-rich slag upgrading dominate cost and emissions. Conversely, a higher-cost H_2 reduction step may be justified if it substantially reduces coke, improves Fe/V recovery, or creates a more valuable Ti product.

To make this flowsheet-level requirement operational, Table 8 defines readiness gates that should be passed before an H_2-assisted VTM route is described as industrially ready. The gates are evidence requirements rather than universal numerical specifications; project-specific pass values must be established for the selected feed, reactor, and downstream destination.

Table 8. *Readiness gates for hydrogen-assisted VTM reduction–smelting routes*

Readiness gate	Minimum evidence to report	Pass condition for scale-up	Principal unresolved risk
Pellet reducibility and disintegration	Metallization, swelling, low-temperature reduction disintegration, strength after reduction, gas composition and temperature	Pellet remains mechanically and hydraulically compatible with the intended shaft or reduction reactor while achieving the required reduction degree	High laboratory reducibility with unacceptable burden degradation or gas-flow instability
Reduction morphology	Fe-domain size/connectivity, pore	Reduced structure supports subsequent	Fine iron-cage structures or trapped gangue/Ti

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Journal International Review of Research Studies
Received: 17/08/2026 - **Accepted:** 17/09/2026
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	evolution, residual oxide and Ti-bearing phase distribution	melting, coalescence, and Fe–Ti separation rather than only high metallization	phases impair downstream separation
Smelting and metal coalescence	Melting sequence, carburization, droplet coalescence/entrainment, tapping yield and residence time	Stable formation and separation of a tappable Fe–C–V phase at representative slag volume	Metal entrainment, refractory interaction, or unstable foaming/tapping
Ti-rich slag quality	TiO_2 grade, FeO, basicity, liquidus/viscosity state, phase assemblage and downstream upgrading response	Slag is operable in the smelter and remains compatible with the intended Ti-recovery or disposal route	V recovery is improved at the expense of unusable Ti slag or excessive viscosity
H_2 and electricity carbon intensity	Hydrogen production pathway, electricity mix, compression/heating, agglomeration and smelting energy	Route-level GHG benefit remains favorable within the declared system boundary and sensitivity range	Low direct carbon use but high upstream electricity/H_2 emissions
Process stability and control	Continuous duration, feed variability, temperature/power control, gas composition, slag state and tapping stability	Key state variables remain observable and controllable over representative campaigns	Short successful tests mask drift in slag oxidation, burden behavior, or energy demand
Downstream product qualification	Full Fe–C–V chemistry, impurity inventory, dissolution/refining behavior and receiving-melt/property validation	Metal and slag products meet the requirements of the declared downstream destination with quantified correction steps	High recovery produces an off-specification metal that requires burdensome refining

Note. Author-developed readiness framework synthesized from the evidence discussed in Section 8, including Chen et al. (2025), H. Liu et al. (2026), Mendoza et al. (2026), Shu et al. (2026), and Zhang et al. (2026). The gates are qualitative audit requirements; they are not validated universal pass/fail thresholds.

Passing a reduction test is therefore only the first gate. An H_2 route becomes credible for scale-up when pellet behavior, reduction morphology, smelting separation, Ti-slag quality, energy/carbon inputs, process stability, and final-product qualification are demonstrated as an integrated sequence.

8.4 Carbon-emission claims require system boundaries

Claims of lower direct fossil-carbon demand should be separated from claims of lower life-cycle greenhouse-gas emissions. Route-level comparisons should specify hydrogen origin, electricity mix, ore upgrading, agglomeration energy, smelting electricity, and downstream V extraction or direct use. Process models of novel low-carbon VTM smelting show that route ranking changes when electricity and reductant assumptions change. The denominator is also important: kg CO_2-

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Received: 17/08/2026 - **Accepted:** 17/09/2026
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eq per tonne of pig iron can obscure whether more or less useful V reaches the final product (Huang et al., 2025; Zhang et al., 2023).

$$CI_{v,useful} = kg\ CO_2\text{-eq} / kg\ V\ retained\ in\ final\ useful\ product \quad (7)$$

9. Vanadium Extraction, Refining, and Direct Steelmaking

9.1 Converter extraction as the established destination

Selective oxidation of V-bearing hot metal remains the established route when the objective is to concentrate vanadium in a processable slag. The process exploits V's strong oxygen affinity and aims to oxidize V before excessive decarburization and iron loss. Temperature, oxygen delivery, stirring, slag formation, and endpoint control govern the V content of semi-steel and the concentration of vanadium oxides in slag (Zhao et al., 2022; Wei et al., 2026).

Industrial process optimization shows that improved bottom stirring and blowing practices can lower residual V in semi-steel and improve vanadium-slag yield. More recent kinetic modeling of mixed CO_2–O_2 injection emphasizes interfacial reactions and emulsified droplets, confirming that converter extraction is not controlled by thermodynamics alone but by bath mixing and interfacial area (Zhao et al., 2022; Wei et al., 2026).

9.2 Selective oxidation when chromium and other alloying elements matter

For V- and Cr-bearing hot metals, the extraction objective can become selective: oxidize V while retaining Cr or limiting losses of other valuable elements. This requires tighter control of oxygen potential and temperature than a simple ‘maximize oxidation’ strategy. Selective-oxidation studies demonstrate that oxidant choice and process staging can alter the V/Cr separation and therefore the value of both metal and slag (Wang et al., 2025).

9.3 Direct steelmaking and direct alloying alternatives

An alternative is to avoid a dedicated vanadium-extraction stage and send V-bearing hot metal directly to steelmaking, producing steel plus a more dilute V-bearing steel slag. This shortens the front-end flowsheet but moves the vanadium-recovery problem to a less concentrated slag. The environmental and economic merit depends on whether the saved extraction step outweighs the

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later cost of recovering V from the steelmaking slag or the value loss if V is not recovered (An et al., 2026; Qiu et al., 2026).

A second alternative is direct vanadium alloying. Self-reducing vanadium-slag briquettes have been used to alloy liquid steel directly, with reported V recovery approaching 90% under optimized laboratory conditions. Although this route differs from adding V-bearing pig iron, it supports a broader principle: intermediate production of purified V_2O_5 and ferrovanadium is not always mandatory when the steel bath can simultaneously act as the reduction and alloying environment (Xin et al., 2021; Xin et al., 2022).

These studies support the metallurgical plausibility of direct vanadium addition but remain indirect evidence for V-bearing pig iron itself. Evidence that vanadium improves cast irons, wear-resistant alloys, or steel chemistry supports application compatibility, but does not by itself validate direct use of a specific V-bearing pig iron product. A deliberately produced Fe–C–V intermediate carries its complete C, Si, S, P, Ti, Cr, Mn, Cu, and Ni inventory into the receiving process unless a separate refining step removes it. The decisive test is therefore not only V recovery to the receiving bath, but whether the complete added mass remains inside the final chemistry and property envelope. If it does not, the route merely transfers refining work downstream and loses its apparent simplicity.

10. Direct Metallurgical Applications of Vanadium-Bearing Pig Iron

10.1 Gray cast iron

Gray cast iron is one of the clearest potential direct-use destinations because carbon and silicon are already integral components of the alloy and because moderate vanadium additions can form VC and refine the matrix. In recent work, increasing V changed graphite morphology, pearlite characteristics, eutectic-cell size, and mechanical properties; tensile strength reached a maximum at an intermediate V level rather than increasing monotonically. This non-monotonic behavior is important because it argues against treating ‘more V’ as automatically better (He et al., 2024).

Tribological testing similarly indicates an optimum rather than a monotonic benefit. A gray cast iron with approximately 0.77 wt% V showed the best wear resistance over multiple test

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Journal International Review of Research Studies
Received: 17/08/2026 - **Accepted:** 17/09/2026
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DOI: 10.66104/qa1tk476
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temperatures, whereas excessive V reduced the benefit. The likely mechanism combines graphite-tip passivation, carbide formation, and resistance to crack propagation (Mao et al., 2025).

10.2 Ductile and austempered ductile iron

Vanadium additions have also been studied in ductile and austempered ductile iron for camshafts and wear-loaded components. V can contribute through carbide formation, pearlite promotion, and precipitation strengthening, but the response depends on heat treatment and the balance between hard phases and matrix toughness. Component-scale testing of low-V alloyed camshafts supports the practical relevance of these effects beyond coupon hardness alone (Colin García et al., 2021; Cruz Ramírez et al., 2023).

10.3 Wear-resistant cast alloys

In wear-resistant irons, the propensity of V to form hard carbides becomes a design feature rather than a refining problem. Studies of indefinite chilled cast iron and other V-alloyed cast systems show improved wear or fracture resistance when carbide population and matrix are properly balanced. However, coarse or excessive carbides can reduce toughness, making V content, solidification rate, and heat treatment interdependent variables (Jiang et al., 2022; Kim et al., 2021; Turu & Gecü, 2023).

Figure 5 summarizes the four principal downstream destinations while deliberately separating metallurgical compatibility from evidence maturity. The diagram is a decision logic, not a statement that all four pathways have equal industrial readiness.

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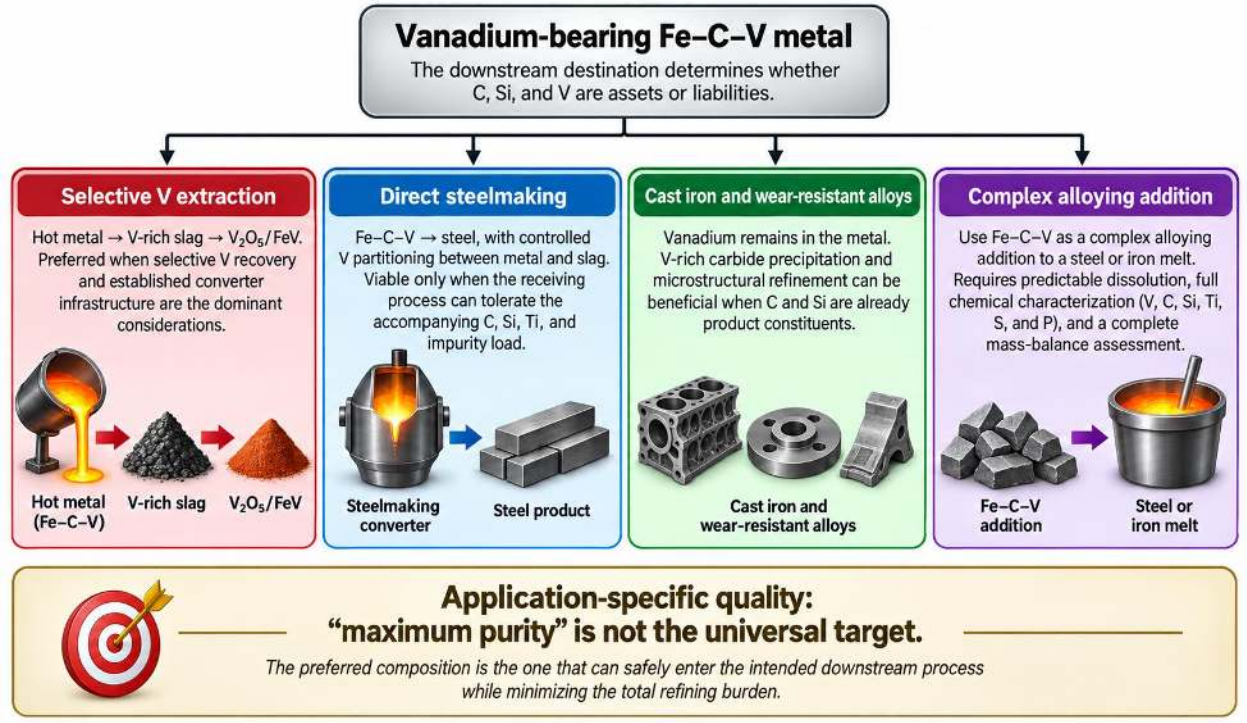

Figure 5. *Direct and indirect metallurgical destinations for vanadium-bearing pig iron*
Note. Author-developed application-screening heuristic based on converter-extraction, direct-alloying, gray-cast-iron, ductile-iron, and wear-resistant-alloy studies (Zhao et al., 2022; Xin et al., 2021; He et al., 2024; Colin García et al., 2021; Kim et al., 2021). It summarizes compatibility logic and does not establish product qualification.

Figure 5 makes the compositional logic explicit. Carbon and silicon that are liabilities for precise steel alloying can be useful constituents in cast iron, whereas sulfur and phosphorus are penalties across most direct-use routes. The optimum Fe–C–V composition is therefore destination-specific, and the direct-use pathway remains conditional until complete impurity and receiving-melt balances are demonstrated.

Table 9 converts this idea into a practical product-quality matrix.

Table 9. *Application-adjusted quality requirements for vanadium-bearing Fe–C–V products*

Destination	Desired attributes	Potential penalties	Relevant performance metric
Converter V extraction	High V inventory; carbon compatible with blowing	P, excessive Ti/Si depending process	V extraction yield; residual V in semi-steel; slag V grade
Direct steelmaking	V compatible with target steel and oxidation schedule	S, P, uncontrolled C/Si/Ti	Steel chemistry; slag V dilution; refining demand

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Complex alloy addition	High V per unit mass; predictable dissolution	S, P, excess C/Si and low V concentration	V recovery to bath; composition correction required
Gray/ductile cast iron	C and Si can be useful; moderate V for microstructure	Excess V/carbide fraction; S/P outside foundry limits	Strength, hardness, graphite/matrix, machinability
Wear-resistant alloy	V carbide-forming capacity is desirable	Brittleness from excessive/coarse carbides	Wear rate, fracture resistance, carbide size/distribution
Further refining to Fe–V intermediate	High V and Fe recovery	S, P, Si increase refining work	Net V yield after refining; energy/reagent burden

Note. Author-developed application-quality screening matrix based on direct pig-iron evidence, converter practice, direct alloying, and cast-iron studies (Romero et al., 2026; Zhao et al., 2022; Xin et al., 2021; He et al., 2024; Kim et al., 2021).

Table 9 shows why maximum chemical purity is not the correct generic objective. The target should be the lowest-cost composition that safely enters the next metallurgical step while meeting final-product performance. This is particularly important for circular secondary-feed routes, where removing every impurity before metal production can destroy the economic advantage of direct recovery.

11. Product Quality, Sustainability, Economics, and Scale-Up

11.1 Product quality must be tied to destination

A Fe–C–V product should be specified using at least V, C, Si, S, P, Ti, Cr, Mn, Cu, and Ni, together with physical form and the intended receiving process. The 2026 secondary-slag product is instructive: V recovery and grade were attractive, but 0.44 wt% S and 6.39 wt% Si meant that desulfurization and chemistry management were prerequisites for broad alloy use. This is not a failure of recovery; it is a destination-specific product-specification issue (Romero et al., 2026). Impurity tolerance must therefore be stated by destination rather than by a universal pig-iron purity target. S and P are generally penalizing because their correction or removal is costly; C and Si can be liabilities in precise steel alloying but useful constituents in cast iron; Ti, Cr, and Mn can be either useful alloying elements or process burdens depending on carbide/nitride formation, oxidation strategy, and target grade; and Cu and Ni are typically retained in the metal and must be treated as grade-dependent residuals or alloying additions rather than assumed removable impurities.

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Journal International Review of Research Studies

Received: 17/08/2026 - **Accepted:** 17/09/2026
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Table 10 converts this qualitative logic into a destination-specific impurity screen. The table intentionally avoids unsupported universal numerical limits: calculate acceptable concentrations from the receiving-melt mass balance and the final product specification.

Table 10. *Destination-specific impurity tolerance and correction logic for Fe–C–V products*

Destination	Potentially useful / tolerable constituents	High-priority penalties	Corrective/refining logic	Qualification requirement
Converter V extraction	High V inventory; C is expected in hot metal; some Mn/Cr may be valuable if selective oxidation is controlled	Excess Si can increase slag burden; S and P remain downstream penalties; Ti can complicate slag/phase behavior	Desiliconization/desulfurization as required; controlled oxidation to transfer V while limiting Fe/Cr loss	Hot-metal chemistry, oxidation kinetics, slag yield/quality, semi-steel specification
Direct steelmaking / complex alloy addition	V is useful; C, Mn, Cr and Ni may contribute if compatible with the steel grade	S and P are stringent penalties; excess C/Si/Ti and uncontrolled Cu/Ni loading can violate grade limits	Dilution, secondary metallurgy, deoxidation/desulfurization, or restricted addition rate based on melt balance	Receiving-melt trials with dissolution yield, V recovery, final chemistry and properties
Gray/ductile cast iron	C and Si are intrinsic; V can strengthen/refine; Mn, Cu or Ni may be useful grade-dependent additions	S and P require control; excess Ti/Cr/V can alter graphite/carbide balance and machinability	Charge blending and inoculation/heat-treatment adjustment rather than maximum purification	Graphite morphology, carbide fraction, matrix, tensile/fatigue/wear properties and casting response
Wear-resistant cast alloys	V, C, Cr and Mn can be intentionally exploited for hard-phase formation; Ni may support matrix design	S and P remain undesirable; excessive Si/Ti or uncontrolled carbide populations can impair toughness	Composition balancing and thermal treatment to control carbide type, size and matrix	Wear, fracture/toughness, hardness, microstructure and component-scale casting validation
Further FeV-like refining / V-chemical chain	High V is advantageous; many co-elements may be correctable if a dedicated refining route is available	High S, P, Si, Ti and tramp-metal loads increase reagent, slag, yield and energy penalties	Oxidation/reduction/refining selected to concentrate V and reject impurities; product yield must be closed	Refining recovery, reagent/energy demand, V-product purity and residue/slag qualification

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Note. Author-developed application-screening matrix synthesized from the evidence in Sections 9–11. Terms such as useful, tolerable, correctable, and penalizing are qualitative and destination dependent; no universal impurity limit is implied.

The decisive distinction is between an impurity that is chemically present and an impurity that is economically or technically disqualifying. A constituent can be acceptable in one destination and prohibitive in another, so recovery data should always be reported together with complete metal chemistry and the intended correction route.

11.2 Sustainability metrics beyond tonnes of pig iron

Published TEA/LCA studies that directly compare alternative Fe–C–V destinations remain sparse. Existing vanadium sustainability and V_2O_5 process studies nevertheless show that roasting chemistry, energy supply, reagent consumption, recycling credits, and coproduct allocation can materially change environmental and economic conclusions. For Fe–C–V routes, system boundaries should extend to the useful final destination because direct use can avoid conversion steps but may also require extra refining, larger alloy-addition mass, or different slag treatment (Petranikova et al., 2020; Zhang et al., 2023). The specific-energy and carbon-normalization expressions below are therefore proposed comparison metrics rather than validated route-ranking thresholds.

Because no single denominator is adequate for every decision boundary, Table 11 specifies complementary functional units and the questions each unit can legitimately answer. Comparative studies should report more than one unit whenever route ranking changes across the value chain.

Table 11. *Recommended functional units for TEA and LCA comparison of Fe–C–V routes*

Functional unit	Primary decision question	Minimum system boundary / data requirement	Main caution
Per tonne VTM feed	How efficiently does the route convert a defined ore or concentrate feed?	Mining/beneficiation boundary declared; feed grade, recovery, agglomeration, reductant, energy, fluxes and residues	Can favor low-value products if product quality and V utilization are not included
Per tonne Fe–C–V product	What is the burden of producing the metallic intermediate?	All steps through tapped/solidified metal; coproduct slag allocation and complete metal chemistry	Different V grades make tonne-of-metal comparisons misleading
Per kg V in tapped metal	What is the cost/energy/carbon burden of first-stage V recovery to metal?	Feed preparation through metal tapping; metal yield and V assay	Does not capture later refining losses or whether tapped V is ultimately useful

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Per kg V retained in useful final product	What is the whole-chain burden of useful vanadium delivery?	All conversion/refining steps through specification-compliant final product; V losses and product qualification	Requires consistent definition of 'useful' and transparent coproduct allocation
Per tonne cast/steel component	What is the burden of a destination-specific final product?	Receiving melt, alloy additions, refining, casting/steelmaking yield, heat treatment where relevant	Product functions and mechanical-property requirements must be comparable
Per tonne avoided FeV equivalent	What is the potential benefit of bypassing conventional V_2O_5/FeV production?	Define equivalent V delivery and alloying performance; include added mass, correction, and handling of Fe–C–V	Avoided-burden credit is scenario dependent and must not exceed the truly displaced conventional route

Note. Author-developed functional-unit framework. The units are complementary rather than interchangeable; studies should declare feed grade, allocation method, electricity/H_2 assumptions, refining steps, final product specification, and the fraction of V retained at the reported boundary.

Accordingly, kg CO_2-eq per tonne of pig iron should not be used alone to support a low-carbon vanadium claim. A route can appear favorable at the intermediate-metal boundary yet lose that advantage after impurity correction, Ti-slag upgrading, or downstream V losses.

$$SEC_e,V = kWh / kg\ V\ retained\ in\ useful\ final\ product \quad (8)$$

$$SEC_c,V = kg\ reductant\ carbon / kg\ V\ retained\ in\ useful\ final\ product \quad (9)$$

11.3 Economics: cost per useful vanadium, not cost per tonne of metal

Techno-economic comparison should include feed preparation, agglomeration, reductant, electricity, fluxes, refractory consumption, metal losses, slag handling, refining, and the credit or cost assigned to Ti-rich and cleaned slag products. Discounted-cash-flow analysis of vanadium extraction from titaniferous slag demonstrates how viability depends on recovery and product-value assumptions. For direct Fe–C–V use, a defensible benchmark is the avoided cost of V_2O_5/FeV production minus the cost of composition correction, refining, and handling the larger alloy-addition mass (Nkosi et al., 2026). At present, the literature is too heterogeneous to support a robust universal economic ranking of the destination options.

$$C_v,delivered = total\ route\ cost / kg\ V\ delivered\ to\ final\ application \quad (10)$$

Report these normalizations together with the system boundary, electricity and hydrogen assumptions, coproduct allocation method, feed grade, scale, and the fraction of vanadium retained in the specification-compliant final product. Without that metadata, apparent cost or carbon advantages are not transferable between routes.

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11.4 Scale-up is preservation of a performance vector

Laboratory scale-up is often described by furnace size, residence time, or throughput. For V-bearing pig iron, true scale-up should instead preserve a performance vector: representative feed mineralogy and PSD; reduction degree and pellet integrity; metal V and C; Ti rejection; slag FeO/basicity/TiO_2; liquidus and viscosity state; metal-droplet entrainment; energy per tonne; specific carbon; impurity levels; stable tapping; and observability of the controlling state variables. Reproducing metal grade alone is insufficient if the slag, separation, energy, or control envelope has changed. The 2 kg induction-smelting scale-up of a secondary-slag mixture is valuable because it moved beyond a small tube-furnace nugget and quantified metal recovery, but it remains far from continuous industrial operation (Romero et al., 2026).

Hydrogen-based VTM development provides a complementary scale-up example. Industrial shaft-furnace trials demonstrated that feed-blend design had to be changed specifically to meet reduction-disintegration and reducibility constraints before electric smelting could be integrated. This is a stronger form of scale-up evidence because it shows that feed design, reactor operation, and downstream smelting must be co-optimized (H. Liu et al., 2026).

Table 12 proposes a minimum metric set for comparing routes at bench, pilot, and industrial scales.

Table 12. *Recommended performance vector for Fe–C–V scale-up and route comparison*

Dimension	Minimum metric	Why it matters
Feed representativeness	Mineralogy, PSD, Fe/V/Ti, gangue, S/P	Avoids scaling an unrepresentative ‘easy’ sample
Reduction	Metallization, disintegration, swelling, Fe-domain morphology	Links kinetics to reactor operability and later separation
Metal product	V, Fe, C, Si, S, P, Ti, Cr, Mn; mass yield	Defines application-adjusted quality
Slag state	FeO, TiO_2, basicity, liquidus, viscosity/flowability	Connects chemistry to tapping and V partitioning
Separation	Metal droplet size/entrainment, settling/tapping yield	Distinguishes physical from chemical metal losses
Energy/carbon	kWh/t Fe–C–V; kWh/kg useful V; kg C/kg useful V	Permits fair comparison of high- and low-V products
Downstream use	Refining steps avoided/required; final V utilization	Prevents first-stage recovery from dominating the decision
Scale evidence	Continuous duration, throughput, availability, control stability	Separates demonstration from industrial readiness

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Note. Author-developed scale-up evidence summary informed by recent VTM smelting, hydrogen-metallurgy, slag-engineering, and scale-up demonstrations (Guo et al., 2026; H. Liu et al., 2026; Romero et al., 2026; Zheng et al., 2026).

Table 12 is deliberately stricter than a conventional recovery table. A route should not be labeled industrially scalable merely because metal grade and recovery increase with furnace size. Scale-up is demonstrated when the coupled product, slag, energy, impurity, control, and separation envelope remains stable over representative feed variability.

11.5 Environmental value of secondary resources

Secondary slag routes can deliver environmental value through avoided landfilling, recovery of Fe and V, reduced virgin flux demand through self-fluxing blends, and creation of a stabilized residual slag. However, those benefits are contingent on the quality and regulatory acceptance of the residue and on the emissions associated with reductant, electricity, and volatilized metals. Circularity should therefore be treated as a mass-and-quality outcome, not as an automatic attribute of using waste feed (Lee et al., 2021; Petranikova et al., 2020; Romero et al., 2026).

12. Critical Synthesis: Vanadium Destination Engineering and Research Gaps

12.1 The decision map

The evidence reviewed here supports three broad destination regions. Region I is V extraction: V-bearing hot metal is oxidized to a concentrated slag when independent V recovery, precise steel chemistry, or an established converter-slag infrastructure has the highest value. Region II is direct Fe–C–V use: vanadium remains in the metal when Fe and C are already useful, V is required in the final alloy, carbide formation is beneficial, and impurity levels can be tolerated or corrected. Region III is direct steelmaking: the dedicated V-extraction step is omitted, but V is partly retained in steel or transferred to a more dilute steelmaking slag. The best region depends on the product specification and the full value chain (Qiu et al., 2026; Romero et al., 2026; Xin et al., 2021).

Figure 6 presents a qualitative Vanadium Destination Map using relative metal V and C contents as visible axes. Numerical ticks and hard boundaries are intentionally omitted because the available evidence does not support universal composition cutoffs. S+P, Si, Ti, Cr, Mn, temperature, dissolution behavior, and receiving-melt requirements remain additional dimensions that can shift the preferred destination.

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Received: 17/08/2026 - **Accepted:** 17/09/2026
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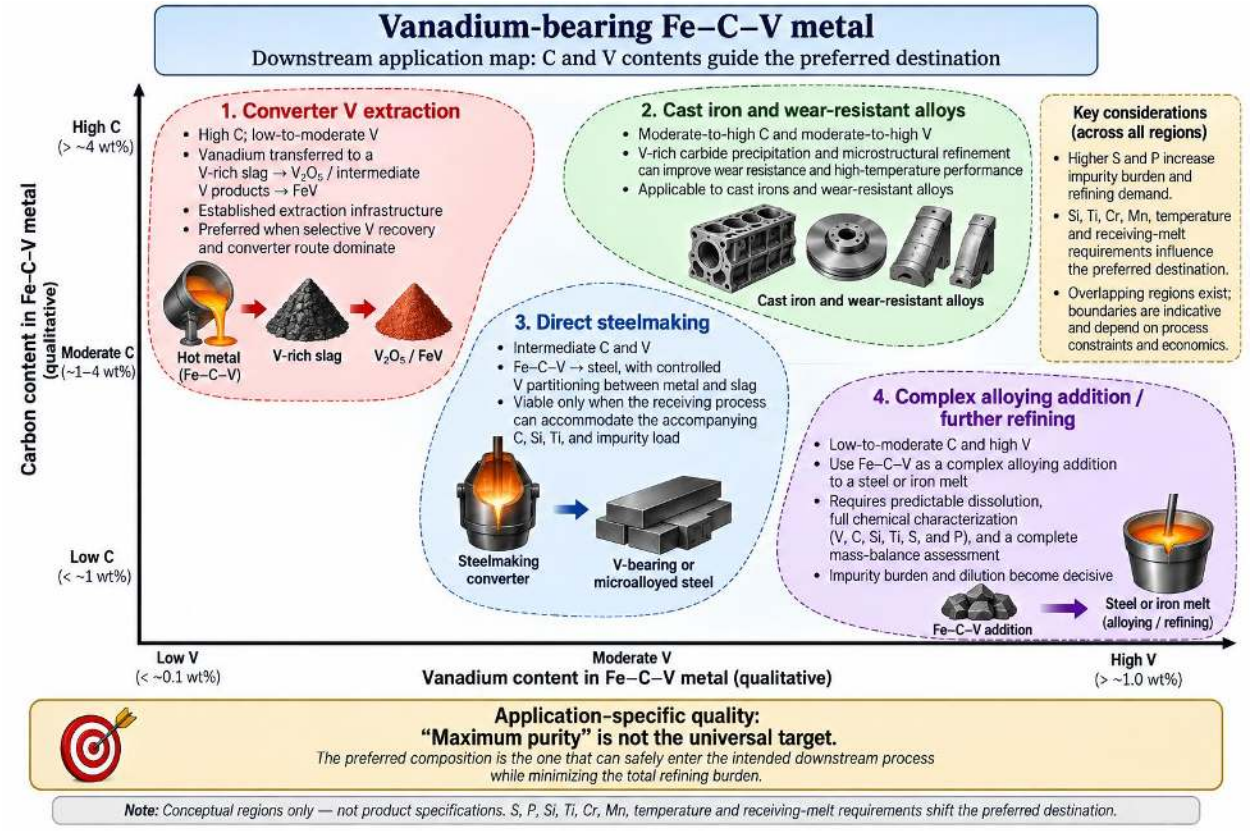

Figure 6. Vanadium Destination Map: qualitative application regions for Fe–C–V products

Note. Author-developed qualitative screening map based on Romero et al. (2026), Guo et al. (2026), He et al. (2024), and the downstream evidence reviewed in Sections 9–11. Regions are application-screening domains, not product standards or validated predictive boundaries; no numerical composition cutoff is implied.

Figure 6 illustrates why a universal minimum V grade for vanadium-bearing pig iron would be misleading. A higher-C metal may be attractive for converter extraction or cast-iron use, whereas a higher-V, lower-impurity metal may be more valuable as an alloying or further-refining feed. The map should therefore evolve into a multidimensional, data-driven decision tool only after sufficient end-to-end datasets become available; until then, interpret it as a hypothesis map rather than a specification chart.

Table 13 operationalizes the Vanadium Destination Engineering Framework as a decision matrix. Because the reviewed literature does not establish universal composition windows for all destinations, the matrix uses destination-specific evidence requirements rather than invented numerical limits. Where a receiving specification exists, calculate the acceptable V and impurity ranges from the actual melt balance and product standard.

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Received: 17/08/2026 - **Accepted:** 17/09/2026
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Table 13. *Vanadium Destination Engineering Decision Matrix*

Intended destination	V requirement / acceptable range	C, Si, S, P, Ti, Cr, Mn, Cu, Ni control	Required correction or refining	V-utilization criterion	Energy/carbon burden to report	Minimum scale-up evidence
Selective oxidation to V slag	High recoverable V inventory preferred; exact range route-specific	C expected; Si/S/P and Ti/Cr behavior must be compatible with converter selectivity and slag practice	Hot-metal pretreatment and controlled V oxidation; downstream slag processing	V recovered into processable slag and subsequently into saleable V product	Per kg V in V-rich slag and per kg V in final V product; include converter/refining energy	At least pilot/industrially representative oxidation behavior; M4–M6 preferred for readiness claims
Direct steelmaking / complex alloy addition	No universal minimum; V addition must satisfy target-steel mass balance without excessive carrier mass	Strict control of S/P; C/Si/Ti/Cr/Mn/Cu/Ni assessed against target grade	Dilution/secondary metallurgy only if economic advantage over FeV route remains	V retained in specification-compliant steel	Per kg useful V and per tonne qualified steel; include avoided FeV credit only when demonstrated	Receiving-melt trials with full chemistry and V yield; M3+ for application claims
Gray/ductile cast iron	Destination-specific V window set by graphite/carbide/property response	C/Si can be beneficial; S/P controlled; Ti/Cr/Mn/Cu/Ni balanced for graphite, carbide and matrix targets	Charge blending, inoculation and heat treatment rather than aggressive purification	V retained in qualified casting with required microstructure/properties	Per kg useful V and per tonne qualified casting	Pilot/component-scale melt and casting validation; M3+ with property evidence
Wear-resistant cast alloy	V set by targeted carbide population and matrix, not a generic pig-iron grade	C/Cr/Mn/V may be intentional; S/P minimized; Ti/Si/Cu/Ni constrained by toughness and matrix design	Composition balancing and heat treatment	V contributing to qualified wear/toughness performance	Per tonne qualified component and per kg V retained	Component-scale casting and service-relevant property testing; M3+; industrial demonstration for product claims
Further refining to FeV/V products	Higher V generally improves feed value, but lower-grade feed may remain viable if refining is efficient	Broad impurity tolerance depends on chosen refining chemistry; high S/P/Si/Ti/tramp loads can raise losses and reagent demand	Dedicated oxidation/reduction, slagging, leaching or alloy refining	V recovered into specification-compliant FeV/V_2O_5 or other V product	Per kg final V product; include residues, reagents and yield loss	Closed mass balance at pilot scale or stronger; M3+ for route comparison

Note. Author-developed application-screening heuristic. The matrix converts the conceptual framework into auditable decision variables, but it is not a product standard or validated predictive model. Numerical composition limits must come from destination-specific specifications and receiving-melt mass balances.

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Journal International Review of Research Studies
Received: 17/08/2026 - **Accepted:** 17/09/2026
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The decision matrix prevents a high-V metal from being classified automatically as the preferred product. The preferred destination preserves the largest fraction of feed V in a qualified final product while minimizing correction steps, impurity penalties, energy use, carbon burden, and scale-up risk.

12.2 The most important unresolved scientific questions

The first unresolved question is quantitative partitioning across realistic feed variability. Most studies change one or two slag variables under controlled laboratory conditions, whereas industrial feed blends change Fe/V/Ti ratio, gangue, basicity demand, oxidation state, and minor-element chemistry together. Transferable models must therefore couple Fe–V–Ti–C–O thermodynamics with slag structure, non-ideal activities, kinetics, and uncertainty (Heo et al., 2021; Wang et al., 2020; Wright & Davidson, 2021; Zheng et al., 2026; Zhou et al., 2026).

The second gap is the physical chemistry of metal separation. Droplet coalescence and settling are known to control metallic recovery in slags, yet many VTM studies report final slag V without distinguishing oxidized V from entrained Fe–C–V. Interfacial tension, droplet-size distributions, turbulence, slag viscosity, and residence-time distributions should become standard scale-up measurements (He et al., 2020; Lai et al., 2026; Zheng et al., 2026).

The third gap is application coupling. Cast-iron studies establish that V can improve microstructure and wear performance, and direct-alloying studies establish that V can be recovered directly into steel. This evidence is valuable but largely indirect for the central Fe–C–V proposition. What is still missing is a controlled end-to-end study that begins with deliberately produced V-bearing pig iron, characterizes the complete impurity inventory, introduces it into a target industrial melt, and closes V, C, Si, S, P, Ti, mass, energy, and final-property balances (Colin García et al., 2021; He et al., 2024; Kim et al., 2021; Xin et al., 2021).

The fourth gap is comparative decarbonization. Hydrogen-assisted reduction is progressing rapidly, but future comparisons must include pellet preparation, H_2 source, electricity, smelting, Ti-slag upgrading, and the downstream vanadium destination. Lower direct fossil-carbon demand must not be equated automatically with lower life-cycle greenhouse-gas emissions. Without a complete and consistent boundary, a low-carbon reduction step may be misinterpreted as a low-

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carbon vanadium value chain (Huang et al., 2025; H. Liu et al., 2026; Shu et al., 2026; Zhang et al., 2023).

Table 14 summarizes the research priorities that most directly determine whether vanadium-bearing pig iron can become an engineered product rather than merely an intermediate.

Table 14. *Priority research gaps for industrial development of vanadium-bearing pig iron*

Priority	Current limitation	Recommended evidence
Standardize product definition	No universal distinction between V-bearing hot metal and deliberately produced Fe–C–V product	Report full metal chemistry, physical form, intended destination, and V recovery
Quantify metal–slag V maps	Sparse comparable data across real feed and slag variability	Generate activity/partition databases with uncertainty and validated thermodynamic models
Separate chemical and physical V losses	Total slag V often conflates oxidized V and entrained metal	Combine slag chemistry with microscopy/XCT/droplet mass balance
Link H_2 reduction to smelting	High metallization does not guarantee good Fe/Ti separation	Measure Fe-domain morphology, coalescence, liquid formation, and smelting response
Control Ti/C/N phases	TiC/Ti(C,N) and V carbides change operation and product behavior	Map carbon/nitrogen activity and cooling history against phase formation
Validate direct Fe–C–V alloy use	Few end-to-end studies from pig iron to final component	Industrial melt trials with full impurity and property balances
Develop application-adjusted specifications	Maximum purity is an inefficient universal target	Define separate quality windows for extraction, steel, cast iron and wear alloys
Improve TEA/LCA boundary consistency	Studies use different denominators and product credits	Report cost and CO_2 per kg V retained in useful final product
Demonstrate continuous scale-up	Most new routes remain batch or short-duration	Long-duration pilot/industrial campaigns under variable feed and closed mass/energy balances

Note. Author-developed critical evidence synthesis based on the evidence reviewed in Sections 3–11 (Guo et al., 2026; H. Liu et al., 2026; Romero et al., 2026; Wang et al., 2020; Xin et al., 2021; Zhang et al., 2023; Zheng et al., 2026).

Table 14 defines a practical research agenda. The highest-value next studies are not additional equilibrium calculations under narrowly controlled conditions, but integrated campaigns that connect representative feed mineralogy, reduction, smelting, metal–slag separation, full product

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Received: 17/08/2026 - **Accepted:** 17/09/2026
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chemistry, downstream use, and economic/environmental metrics. Such studies would allow the Vanadium Destination Map to evolve from a conceptual framework into a predictive design tool.

12.3 Limitations of the Review and Evidence Base

This review has several limitations that should bound interpretation of its framework. First, it is a structured critical review rather than a prospectively registered systematic review. The search logic, Boolean families, eligibility rules, source-level matrix, and narrative selection flow are now reported for auditability, but we did not retain historical gross search counts or a complete prospective exclusion log, and we cannot reconstruct them retrospectively. Google Scholar was the primary discovery platform, with publisher/DOI verification and citation chaining; consequently, the corpus should not be interpreted as an exhaustive database census.

Second, the relevance and maturity tags are author-developed interpretive classifications assigned by a single reviewer-author. They were not independently recoded, and we do not report Cohen's kappa, Krippendorff's alpha, or an equivalent inter-rater statistic. The full assignments are therefore provided in Supplementary Table S1 so the synthesis remains auditable, rather than presenting the taxonomy as an independently validated measurement instrument.

Third, the evidence base is heterogeneous in feed mineralogy, reactor scale, slag chemistry, temperature, reductant, analytical methods, and downstream product definition. Direct comparison of numerical recoveries across studies is therefore inappropriate unless feed basis, phase definition, scale, and system boundary are harmonized. Several rapidly evolving 2026 studies are laboratory, pilot, demonstration, or advanced-online records, which further limits claims of settled industrial maturity.

Fourth, direct end-to-end validation remains sparse. Evidence that vanadium improves cast irons, wear-resistant alloys, or steel chemistry demonstrates application compatibility but does not by itself qualify a deliberately produced Fe–C–V pig iron carrying its complete impurity inventory. Likewise, successful H_2 reduction does not establish integrated smelting, Ti-slag quality, product qualification, or life-cycle superiority. The Vanadium Destination Map and Decision Matrix should therefore be used as qualitative screening frameworks until receiving-melt trials, continuous campaigns, and route-comparable TEA/LCA data provide stronger validation.

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Received: 17/08/2026 - **Accepted:** 17/09/2026
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13. Conclusions

Vanadium-bearing pig iron occupies a strategic position between mineral processing, ironmaking, vanadium extraction, and alloy design. The evidence reviewed here shows that the Fe–C–V metallic phase should not be defined solely as an intermediate that must be oxidized to produce a vanadium slag. In some flowsheets, selective oxidation remains the technically and economically preferred destination; in others, retaining vanadium in the metal can shorten the route and create a directly useful alloying or cast-iron resource.

The governing principle is vanadium destination engineering. Feed mineralogy determines how Fe, V, and Ti enter the reduction pathway; reduction chemistry determines the extent and morphology of metallization; slag chemistry and oxygen potential control chemical partitioning; viscosity, interfacial phenomena, and residence time control physical metal recovery; and final C, Si, S, P, Ti, Cr, and V contents determine whether the metal is a product or merely another intermediate. No single recovery number captures this chain.

Hydrogen-assisted reduction is especially promising because it can reduce direct carbon demand and enable integration with electric smelting, but its industrial value depends on pellet integrity, metallic-domain morphology, electricity and hydrogen supply, and the quality of both Fe–V metal and Ti-rich slag. Secondary-slag smelting is similarly promising for circularity but remains constrained by impurity management and continuous-scale validation.

Future development should therefore prioritize end-to-end demonstrations and application-adjusted specifications. The preferred route maximizes the fraction of feed vanadium retained in a useful final product at acceptable cost, energy use, carbon intensity, and operational risk. Under that criterion, vanadium-bearing pig iron is best understood not as a fixed product grade but as a controllable metallurgical platform whose optimal composition depends on the destination.

Declarations

Funding

This review received no specific external funding.

Conflict of Interest

The author declares no conflict of interest.

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Received: 17/08/2026 - **Accepted:** 17/09/2026
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Data Availability

No new experimental datasets were generated. All quantitative values discussed in the review are traceable to the cited literature; Section 2 reports the search logic, inclusion rules, and evidence-grading framework used for the final corpus.

Author Contributions

Author contributions will be disclosed after peer review.

References

An, X., Li, C., Jiang, T., Wen, J., Zhang, L., Yu, T., Hao, G., & Liu, X. (2026). Sustainable recovery of vanadium via synergistic utilization of vanadium slag and vanadium-bearing steel slag. Journal of Environmental Chemical Engineering. Advance online publication. https://doi.org/10.1016/j.jece.2026.123703

Åström, E., Andersson, A., Björkman, B., & Björkvall, J. (2025). Influence of vanadium oxide on the viscosity within the CaO–SiO_2–"FeO"–MgO system. *Metallurgical and Materials Transactions B, 56*, 821–832. https://doi.org/10.1007/s11663-024-03322-9

Bian, Z., Cao, L., Chen, D., Zhao, H., Qi, T., Wang, L., & Zhen, Y. (2023). Titanium impurity control in V-bearing pig iron prepared via the sodium smelting of vanadium–titanium magnetite. *Metals, 13*(9), Article 1620. https://doi.org/10.3390/met13091620

Cao, L., Chen, D., Sang, X., Zhao, H., Zhen, Y., Wang, L., Liu, Y., Meng, F., & Qi, T. (2023). Direct evidence for phase transition process of VC precipitation from $(Fe,V)_3C$ in low-temperature V-bearing molten iron. *Crystals, 13*(2), Article 175. https://doi.org/10.3390/cryst13020175

Chen, L., Deng, G., Wang, Z., Zhang, K., Cao, L., Luo, H., Guo, A., Pu, F., Luo, D., & Liang, B. (2025). Hydrogen-based direct reduction of vanadium-titanium magnetite raw ore: Process optimization and mechanism insights. *Chemical Engineering Journal, 505*, Article 159152. https://doi.org/10.1016/j.cej.2024.159152

Chen, W., Dong, Z., & Wang, X. (2022). Thermodynamic analysis of the reduction of vanadium-titanium magnetite by gasification gas. *ISIJ International, 62*(9), 1816–1826. https://doi.org/10.2355/isijinternational.0_ISIJINT-2022-182

Colin García, E., Cruz Ramírez, A., Reyes Castellanos, G., Téllez Ramírez, J., & Magaña Hernández, A. (2021). Microstructural and mechanical assessment of camshafts produced by ductile cast iron low alloyed with vanadium. *Metals, 11*(1), Article 146. https://doi.org/10.3390/met11010146

Cruz Ramírez, A., Colin García, E., Téllez Ramírez, J., & Magaña Hernández, A. (2023). Performance evaluation of austempered ductile iron camshaft low alloyed with vanadium on an electric spin rig test. *Metals, 13*(2), Article 198. https://doi.org/10.3390/met13020198

Davis, J. R. (Ed.). (1996). ASM specialty handbook: Cast irons. ASM International.

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JIRRS
Journal International Review of Research Studies

Received: 17/08/2026 - **Accepted:** 17/09/2026
Vol: 01.09
DOI: 10.66104/qa1tk476
Pages: 1-48

Fang, M., Dang, Q., & Wang, M. (2026). Process mineralogy of titanomagnetite ore in the Damiao Deposit, Chengde. *Minerals, 16*(8), Article 825. https://doi.org/10.3390/min16080825

Gao, X., Zhang, R., You, Z., Yu, W., Dang, J., & Bai, C. (2022). Use of hydrogen-rich gas in blast furnace ironmaking of V-bearing titanomagnetite: Mass and energy balance calculations. *Materials, 15*(17), Article 6078. https://doi.org/10.3390/ma15176078

Gilligan, R., & Nikoloski, A. N. (2020). The extraction of vanadium from titanomagnetites and other sources. *Minerals Engineering, 146*, Article 106106. https://doi.org/10.1016/j.mineng.2019.106106

Gupta, C. K., & Krishnamurthy, N. (1992). Extractive metallurgy of vanadium. Elsevier.

Guo, X., Dai, S., & Wang, Q. (2020). Influence of different comminution flowsheets on the separation of vanadium titano-magnetite. *Minerals Engineering, 149*, Article 106268. https://doi.org/10.1016/j.mineng.2020.106268

Guo, Z., Chen, X., Shi, Y., Zhu, D., Pan, J., Yang, C., Li, S., Xu, J., & Wang, X. (2025). Smelting separation behaviors of various reduced vanadium titanomagnetite pellets. *Transactions of Nonferrous Metals Society of China, 35*(11), 3869–3885. https://doi.org/10.1016/S1003-6326(25)66918-4

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

Han, Y.-C., Dou, Z., Yang, Z.-N., Xie, W., & Zhang, T.-A. (2025). Process mechanism research on direct vortex melting reduction of vanadium-titanium magnetite. *Journal of Iron and Steel Research International, 32*(3), 536–549. https://doi.org/10.1007/s42243-024-01290-7

He, M., Wang, N., Hou, Q., Chen, M., & Yu, H. (2020). Coalescence and sedimentation of liquid iron droplets during smelting reduction of converter slag with mechanical stirring. *Powder Technology, 362*, 550–558. https://doi.org/10.1016/j.powtec.2019.12.020

He, W., Deng, Y., Chen, J., Qin, Y., Zhang, M., Liu, G., Li, H., & Jing, Z. (2026). Effect of gas mixtures on the reduction and carburization behaviors of vanadium titanomagnetite pellets in H_2–CO–CH_4–H_2O–CO_2–N_2 atmospheres. Ironmaking & Steelmaking. Advance online publication. https://doi.org/10.1177/03019233261417708

He, Y., Chen, C., & Yang, X. (2023). Thermodynamic analysis of vanadium distribution behavior in blast furnaces and basic oxygen furnaces. *High Temperature Materials and Processes, 42*(1), Article 20220259. https://doi.org/10.1515/htmp-2022-0259

He, Y., Mao, F., Gao, A., Pan, K., Guo, A., Liu, S., Wei, S., Chen, C., Zhang, C., Jiang, T., & Wang, C. (2024). The influence of trace vanadium on the solidification process, microstructure, and mechanical properties of gray cast iron. *Journal of Materials Research and Technology, 31*, 998–1007. https://doi.org/10.1016/j.jmrt.2024.06.103

Heo, J., Lee, Y., Park, H., & Park, J. H. (2021). Influence of slag composition and oxygen potential on thermodynamic behavior of vanadium in FeO–TiO_2–MgO–SiO_2–Al_2O_3 smelting slag and

JIRRS
Journal International Review of Research Studies

Received: 17/08/2026 - **Accepted:** 17/09/2026
Vol: 01.09
DOI: 10.66104/qa1tk476
Pages: 1-48

molten iron. *Journal of Materials Research and Technology, 15*, 5723–5732. https://doi.org/10.1016/j.jmrt.2021.11.035

Hu, Q., Xin, R., Gao, X., Wang, Y., You, Y., You, Z., & Lv, X. (2023). Reduction disintegration behavior of vanadium titanomagnetite pellets in H_2–CO–CO_2–N_2 mixtures. *Powder Technology, 413*, Article 118073. https://doi.org/10.1016/j.powtec.2022.118073

Huang, Y., Tang, J., & Chu, M. (2025). Modeling and carbon emission assessment of novel low-carbon smelting process for vanadium–titanium magnetite. *Metals, 15*(4), Article 461. https://doi.org/10.3390/met15040461

Ji, X., Gao, J., Guo, L., Lan, X., Zhang, Y., & Guo, Z. (2026). Ex-situ same-spot investigation of phase evolution and elemental migration in hydrogen-reduced vanadium-titanium magnetite pellets. Minerals Engineering. Advance online publication. https://doi.org/10.1016/j.mineng.2026.110481

Jiang, T., Wei, S., Xu, L., Zhang, C., Wang, X., Xiong, M., Mao, F., & Chen, C. (2022). The effect of vanadium content coupling with heat treatment process on the properties of low-vanadium wear-resistant alloy. *Materials, 15*(1), Article 285. https://doi.org/10.3390/ma15010285

Kim, S. H., Baek, E. R., & Jang, B. K. (2021). The effect of vanadium addition on the fracture and wear resistance of indefinite chilled cast iron. *Materials Today Communications, 26*, Article 101819. https://doi.org/10.1016/j.mtcomm.2020.101819

Lai, C., Jing, B., Tan, J., & Li, Q. (2026). Investigation of iron droplets assembling in molten slag. *Colloids and Surfaces A: Physicochemical and Engineering Aspects, 735*, Article 139463. https://doi.org/10.1016/j.colsurfa.2026.139463

Lee, J.-C., Kurniawan, Kim, E.-Y., Chung, K. W., Kim, R., & Jeon, H.-S. (2021). A review on the metallurgical recycling of vanadium from slags: Towards a sustainable vanadium production. *Journal of Materials Research and Technology, 12*, 343–364. https://doi.org/10.1016/j.jmrt.2021.02.065

Li, H., Li, X., Liu, X., Bu, X., Chen, S., Lyu, Q., & Wang, K. (2023). Prediction of the vanadium content of molten iron in a blast furnace and the optimization of vanadium extraction. *Separations, 10*(10), Article 521. https://doi.org/10.3390/separations10100521

Li, J., Li, W., Zhu, Y., & Wu, X. (2020). Beneficiation of a vanadium-titanium magnetite in Panxi. *Iron Steel Vanadium Titanium, 41*(6), 66–73. https://doi.org/10.7513/j.issn.1004-7638.2020.06.013

Li, J., Men, J., Yang, S., & Zhou, M. (2021). Influence of fuel level on properties, productivity, and mineralogy of Russian vanadiferous titanomagnetite sinter. *Materials, 14*(21), Article 6258. https://doi.org/10.3390/ma14216258

Liu, H., Manojlovic, V., Wang, S., Ji, H., Li, R., Gao, Y., & Gao, M. (2026). An integrated hydrogen metallurgy route of vanadium–titanium magnetite for efficient recovery of Fe, V, and Ti. *Minerals, 16*(2), Article 177. https://doi.org/10.3390/min16020177

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JIRRS
Journal International Review of Research Studies

Received: 17/08/2026 - **Accepted:** 17/09/2026
Vol: 01.09
DOI: 10.66104/qa1tk476
Pages: 1-48

Liu, J., Xing, Z., Cheng, G., Xue, X., & Ding, X. (2022). Study on the grinding kinetics and magnetic separation of low-grade vanadiferous titanomagnetite concentrate. *Metals, 12*(4), Article 575. https://doi.org/10.3390/met12040575

Liu, S., Wang, J., Ye, L., & Bian, Z. (2026). Oxidant-driven vanadium extraction: Critical analysis of current methodologies and sustainable practices. *Minerals Engineering, 242*, Article 110195. https://doi.org/10.1016/j.mineng.2026.110195

Lv, H., Gan, M., Wen, X., Ji, Z., Fan, X., Li, S., Li, J., Wang, S., Wang, X., & Xie, L. (2024). Promoting low-temperature consolidation of vanadium titano-magnetite pellets by high-pressure grinding roll: Mechanism of mechanical activation. *Journal of Materials Research and Technology, 30*, 2435–2445. https://doi.org/10.1016/j.jmrt.2024.03.243

Ma, H., Chen, C., & Zhang, J. (2025). Feasibility study of HIsmelt smelting of vanadium–titanium magnetite based on slag viscosity: Influence of slag chemistry on its fluidity. Ironmaking & Steelmaking. Advance online publication. https://doi.org/10.1177/03019233241309814

Mao, F., He, Y., Guo, A., Wang, X., Zhong, Y., Huang, Z., Chen, C., & Wei, S. (2025). Effect of vanadium and temperature on the tribological properties of gray cast iron. *Journal of Materials Research and Technology, 38*, 3578–3590. https://doi.org/10.1016/j.jmrt.2025.08.211

Mendoza, S., Garlick, C., Singh, T., Nusheh, M., Yin, B. H., Honeyands, T., & Bumby, C. W. (2026). Melting behavior of hydrogen-reduced vanadium-bearing titanomagnetite ironsand pellets in a laboratory-scale electrode smelter. Journal of Sustainable Metallurgy, 12, 1176–1188. https://doi.org/10.1007/s40831-025-01389-5

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

Petranikova, M., Tkaczyk, A. H., Bartl, A., Amato, A., Lapkovskis, V., & Tunsu, C. (2020). Vanadium sustainability in the context of innovative recycling and sourcing development. *Waste Management, 113*, 521–544. https://doi.org/10.1016/j.wasman.2020.04.007

Qin, J., Wang, Y., You, Z., Wen, L., & Lv, X. (2020). Carbonization and nitridation of vanadium-bearing titanomagnetite during carbothermal reduction with coal. *Journal of Materials Research and Technology, 9*(3), 4272–4282. https://doi.org/10.1016/j.jmrt.2020.02.053

Qiu, Y., Sun, Y., Han, Y., & Gao, P. (2026). Advances in vanadium recovery from basic oxygen furnace vanadium slag: Mechanisms, extraction technologies, and emerging strategies. *Journal of Environmental Chemical Engineering, 14*(2), Article 121965. https://doi.org/10.1016/j.jece.2026.121965

Romero, J. L., Recksiek, V., Debastiani, R., Hossain, M. N., Blenau, L., Charitos, A., Vaisanen, A. O., & Patil, A. B. (2026). Pyrometallurgical valorization of Waelz, fayalite, and Linz-Donawitz slag mixtures. *Scientific Reports, 16*, Article 9539. https://doi.org/10.1038/s41598-026-44763-3

Sadangi, J. K., Pati, S., & Biswal, S. K. (2026). Development of suitable process for beneficiation of low-grade vanadium titanomagnetite ore to enhance the vanadium, titanium, and iron

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JIRRS
Journal International Review of Research Studies

Received: 17/08/2026 - **Accepted:** 17/09/2026
Vol: 01.09
DOI: 10.66104/qa1tk476
Pages: 1-48

content. *Transactions of the Indian Institute of Metals, 79*(3), 41. https://doi.org/10.1007/s12666-026-03798-w

Shi, J., Xu, Q., Lu, X., Cao, Z., Kang, H., Chen, B., & Guo, L. (2024). Influence of preoxidation treatment on the reduction behavior and reaction kinetics of vanadium titanomagnetite by hydrogen. *The Journal of Physical Chemistry C, 128*(18), 7536–7548. https://doi.org/10.1021/acs.jpcc.4c01078

Shi, J., Xu, Q., Lu, X., Cao, Z., Kang, H., Chen, B., & Guo, L. (2025). Effect of H_2/CO ratio on non-isothermal reduction behavior and kinetics of vanadium titanomagnetite. *International Journal of Hydrogen Energy, 139*, 69–79. https://doi.org/10.1016/j.ijhydene.2025.04.280

Shu, Y., Zhang, H., Shen, X., Chen, M., Zhang, Y., Yi, L., Li, G., & Jiang, T. (2026). New insights into the H_2/CO functional gap in vanadium-titanomagnetite reduction: Linking microstructural evolution to kinetics mechanism. Minerals Engineering. Advance online publication. https://doi.org/10.1016/j.mineng.2026.110595

Sun, G., Shi, Z., Ma, H., Xu, W., & Han, S. (2026). Thermodynamic analysis of V, Cr, and Ti distribution in electric furnace smelting of V-Ti DRI. *Metals, 16*(8), Article 831. https://doi.org/10.3390/met16080831

Turu, I. C., & Gecü, R. (2023). Wear and corrosion behavior of vanadium-alloyed nodular cast irons fabricated by sand-casting. Wear, 534–535, Article 205143. https://doi.org/10.1016/j.wear.2023.205143

Turkdogan, E. T. (1996). Fundamentals of steelmaking. Institute of Materials.

van Gerve, T. D., Muchez, P., Nuorivaara, T., & Namur, O. (2026). The impact of exsolution textures in Fe–Ti oxide minerals on crushing strategies and vanadium and titanium pre-concentration. *European Journal of Mineralogy, 38*, 545–556. https://doi.org/10.5194/ejm-38-545-2026

Verein Deutscher Eisenhüttenleute (Ed.). (1995). Slag atlas (2nd ed.). Verlag Stahleisen.

Vickerfält, A., Martinsson, J., & Sichen, D. (2021). Effect of reduction degree on characteristics of slag formed by melting hydrogen-reduced DRI and partitions of P and V between slag and metal. *Steel Research International, 92*(3), Article 2000432. https://doi.org/10.1002/srin.202000432

Wang, S., Guo, Y., Zheng, F., Chen, F., Yang, L., Jiang, T., & Qiu, G. (2020). Behavior of vanadium during reduction and smelting of vanadium titanomagnetite metallized pellets. *Transactions of Nonferrous Metals Society of China, 30*(6), 1687–1696. https://doi.org/10.1016/S1003-6326(20)65330-4

Wang, X.-Y., Zhao, H.-Q., Wang, L.-F., Liu, Q.-C., Yan, D.-L., Wang, F., & Qi, Y.-H. (2025). Selective oxidation control for synchronous vanadium extraction and chromium retention from vanadium- and chromium-bearing hot metal. *Metals, 15*(11), Article 1275. https://doi.org/10.3390/met15111275

Wang, Y.-H., Wang, Y.-F., Li, Y.-T., Wu, C., Han, X.-L., Zhao, N.-N., Zhang, Z.-K., Dai, L., Wang, L., & He, Z.-X. (2024). A review on vanadium extraction techniques from major

CC BY

JIRRS
Journal International Review of Research Studies

Received: 17/08/2026 - **Accepted:** 17/09/2026
Vol: 01.09
DOI: 10.66104/qa1tk476
Pages: 1-48

vanadium-containing resources. *Rare Metals, 43*(9), 4115–4131. https://doi.org/10.1007/s12598-024-02721-w

Wei, G., Wang, H., Ju, J., Yang, Y., & Jiang, X. (2026). Kinetic model for vanadium extraction by CO_2–O_2 mixed injection based on interfacial reactions of emulsified droplets. *Metallurgical and Materials Transactions B, 57*(9), 5480. https://doi.org/10.1007/s11663-026-04188-9

Wright, S., & Davidson, R. (2021). Distribution of vanadium between Al_2O_3–CaO–MgO–SiO_2–TiO_2 slag and carbon saturated iron. *Mineral Processing and Extractive Metallurgy, 130*(4), 302–312. https://doi.org/10.1080/25726641.2019.1633505

Xin, J., Wang, N., Chen, M., & Chen, C. (2021). Direct alloying of molten steel with vanadium slag as a substitute of ferrovanadium: Self-reduction behavior of vanadium slag briquette with aluminum dross addition. *Metallurgical and Materials Transactions B, 52*(2), 815–829. https://doi.org/10.1007/s11663-020-02055-9

Xin, J., Wang, N., Chen, M., & Chen, C. (2022). Direct vanadium alloying of liquid steel with self-reducing vanadium slag briquette. *Steel Research International, 93*(6), Article 2100609. https://doi.org/10.1002/srin.202100609

Yang, M.-Q., & Yang, J.-Y. (2024). Vanadium extraction from steel slag: Generation, recycling and management. *Environmental Pollution, 343*, Article 123126. https://doi.org/10.1016/j.envpol.2023.123126

Yang, S., Tang, W., & Xue, X. (2021). Effect of TiO_2 on the sintering behavior of low-grade vanadiferous titanomagnetite ore. *Materials, 14*(16), Article 4376. https://doi.org/10.3390/ma14164376

Yu, H.-D., Wang, L.-N., Qu, J.-K., & Qi, T. (2020). Process mineralogical characteristics and ore value of typical vanadium titanium magnetite in China. *Journal of Northeastern University Natural Science, 41*(2), 275–281. https://doi.org/10.12068/j.issn.1005-3026.2020.02.022

Yu, J., Ou, Y., Sun, Y., Li, Y., & Han, Y. (2022). Hydrogen reduction behaviors and mechanisms of vanadium titanomagnetite ore under fluidized bed conditions. *Powder Technology, 402*, Article 117340. https://doi.org/10.1016/j.powtec.2022.117340

Zhang, G., Wang, Y., Meng, X., Zhang, D., Ding, N., Ren, Z., Gao, W., & Sun, Z. (2023). Life cycle assessment on the vanadium production process: A multi-objective assessment under environmental and economic perspectives. *Resources, Conservation and Recycling, 192*, Article 106926. https://doi.org/10.1016/j.resconrec.2023.106926

Zhang, S., Hu, P., Rao, J., Wang, Z., Zong, Y., & Zhang, J. (2022). Effect of smelting time on vanadium and titanium distribution behavior and slag viscosity in HIsmelt. *Metals, 12*(6), Article 1019. https://doi.org/10.3390/met12061019

Zhang, S., Wang, Z., Hu, P., Rao, J., Zhang, J., & Pang, J. (2022). Distribution behavior of vanadium and titanium between hot metal and high titanium slag relevant to HIsmelt smelting condition. *Journal of Materials Research and Technology, 19*, 4517–4524. https://doi.org/10.1016/j.jmrt.2022.07.020

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JIRRS
Journal International Review of Research Studies

Received: 17/08/2026 - **Accepted:** 17/09/2026
Vol: 01.09
DOI: 10.66104/qa1tk476
Pages: 1-48

Zhang, S., Wang, Z., Zhang, J., Guo, P., Jiang, D., & Si, R. (2024). Effect of TiO_2 and FeO on viscosity and structure of HIsmelt titanium-containing slag. *Ceramics International, 50*(1), 791–798. https://doi.org/10.1016/j.ceramint.2023.10.163

Zhang, S., Zhang, J., Wang, Z., Guo, P., Zhang, S., Huang, Y., & Sun, Q. (2026). Softening-melting behavior and phase evolution mechanism of vanadium-titanium magnetite burden under oxygen blast furnace conditions. *International Journal of Hydrogen Energy, 197*, Article 152710. https://doi.org/10.1016/j.ijhydene.2025.152710

Zhao, J., Wu, W., Zhao, B., Li, X., & Xiao, F. (2022). Influence of vanadium extraction converter process optimization on vanadium extraction effect. *Metals, 12*(12), Article 2061. https://doi.org/10.3390/met12122061

Zheng, F., Hu, B., Chen, G., Liu, C., Wei, J., Zhang, C., Yang, D., & He, F. (2026). Process optimization of slag composition for improved vanadium recovery and slag–iron separation in V–Ti magnetite smelting. Steel Research International. Advance online publication. https://doi.org/10.1002/srin.202501151

Zhou, H., Guo, J., Hou, Y., Hu, X., Dang, J., & Lv, X. (2026). Effect of FeO content on the fluidity of high-TiO_2 slag and vanadium distribution behavior during electric furnace smelting process. *Metallurgical and Materials Transactions B, 57*(9), 5266–5282. https://doi.org/10.1007/s11663-026-04170-5

Zhu, F., Ma, Z., Gao, G., Qiu, K., & Peng, W. (2023). Process mineralogy of vanadium titanomagnetite ore in Panzhihua, China. *Separations, 10*(3), Article 147. https://doi.org/10.3390/separations10030147

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