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Roasting-Assisted Beneficiation of Magnetite–Apatite Ores: Phase Transformations, Phosphorus Partition, And Selective Recovery

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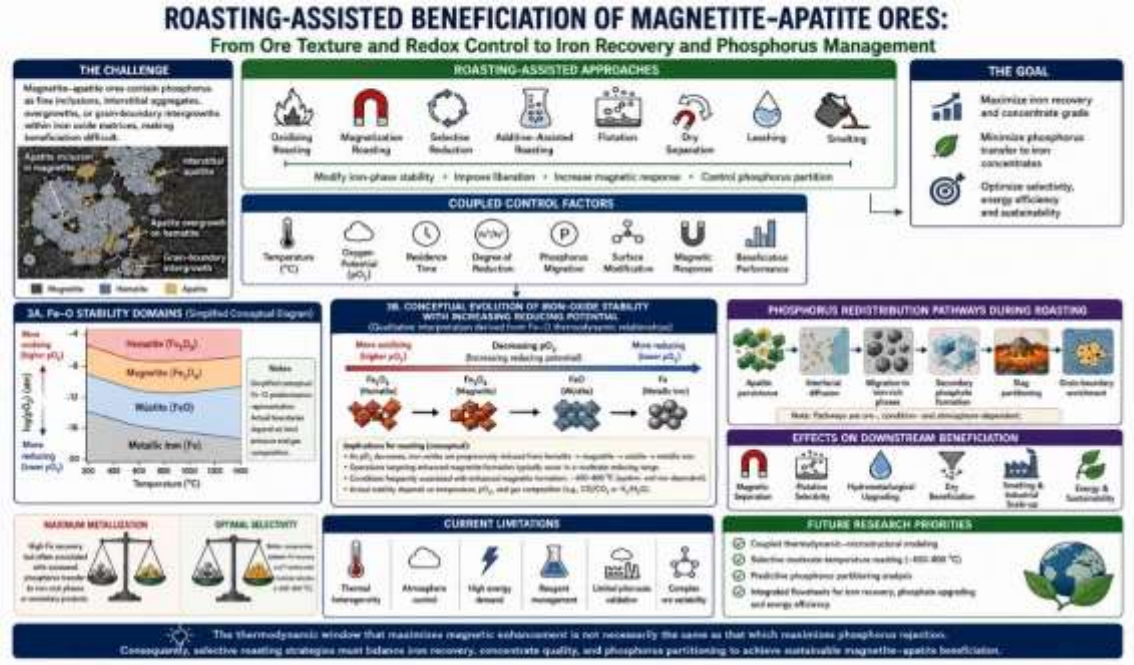
ABSTRACT: Magnetite–apatite ores constitute important resources of both iron and phosphorus but remain challenging to beneficiate because phosphorus-bearing phases commonly occur as finely disseminated apatite, interstitial aggregates, hydrothermal overgrowths, and complex grain-boundary intergrowths within iron oxide matrices. Roasting-assisted beneficiation has emerged as a promising strategy for modifying iron mineralogy, enhancing magnetic susceptibility, improving mineral liberation, and controlling phosphorus distribution. However, existing studies remain dispersed across the following routes: oxidizing roasting, magnetization roasting, selective reduction, additive-assisted roasting, flotation, leaching, dry beneficiation, and smelting. This critical review examines the interactions among ore texture, oxygen potential, roasting temperature, residence time, degree of reduction, phosphorus migration, and beneficiation performance. Particular attention is given to moderate-temperature reduction (approximately 650–800 °C), which frequently provides a more favorable balance between iron recovery and phosphorus rejection than highly reducing metallization-oriented conditions. Thermodynamic and kinetic aspects of the hematite–magnetite–wüstite–metallic iron transformation are discussed together with phosphorus redistribution mechanisms, including apatite preservation, interfacial diffusion, secondary phosphate formation, metallic iron contamination, slag partitioning, and leaching behavior. Comparative analysis indicates that maximum metallization does not necessarily yield optimal beneficiation outcomes, as excessive reduction often promotes the incorporation of phosphorus into metallic iron. Current industrial implementation remains limited by thermal heterogeneity, atmosphere control, energy consumption, and insufficient pilot-scale validation. Future advances require integrated thermodynamic–microstructural modeling, predictive approaches to phosphorus partitioning, and energy-efficient roasting flowsheets that simultaneously enhance iron recovery and phosphorus management.

KEYWORDS: magnetite–apatite ores; roasting beneficiation; phosphorus partition; selective reduction; thermal activation; apatite flotation

HIGHLIGHTS

- Moderate-temperature roasting between 650 and 800 °C can improve the balance between iron recovery and phosphorus selectivity.
- Oxygen potential and reduction degree strongly influence phosphorus redistribution toward metallic iron.
- Roasting modifies flotation selectivity through coupled mineralogical, microstructural, and surface-chemical effects.
- Aggressive reduction improves metallization but frequently decreases phosphate purity.
- Industrial implementation remains constrained by thermal heterogeneity, energy demand, and limited pilot-scale validation.

Graphical abstract



1. INTRODUCTION

Magnetite–apatite ores constitute important strategic resources because they simultaneously contain iron-bearing minerals and phosphate-rich phases. These ores are commonly associated with iron oxide–apatite systems, Kiruna-type mineralization, magmatic-hydrothermal environments, hydrothermal overprinting, and metasomatic alteration processes (Apukhtina et al., 2016; He et al., 2018; Tornos et al., 2017). Their importance extends beyond conventional iron ore beneficiation, as apatite-bearing fractions may also represent phosphate resources, especially when circular use of mineral resources and critical raw material security are considered (Tornos et al., 2021, 2024).

The origin and evolution of magnetite–apatite systems remain debated. Magmatic, magmatic-hydrothermal, hydrothermal replacement, and immiscibility-related models have been proposed for different deposits. Trace-element and isotopic studies of magnetite and apatite have shown that these systems may form through a continuum of igneous and hydrothermal processes rather than a single genetic mechanism (Broughm et al., 2017; Ghazi et al., 2019; Heidarian et al., 2016; Nie et al., 2017; Pietruszka et al., 2023; Rodríguez-Mustafa et al., 2020; Salazar et al., 2024). This genetic diversity is not only of geological interest. It directly affects beneficiation because mineral chemistry, apatite morphology, gangue assemblage, and alteration intensity control liberation, roasting response, and phosphorus mobility.

Beneficiation difficulty mainly stems from textural complexity. Phosphorus-rich minerals may be discrete apatite grains, inclusions within magnetite, interstitial aggregates, fracture fillings, or secondary phases. Studies of apatite–magnetite ores and tailings show that liberation can remain incomplete even after fine grinding when apatite is encapsulated within iron oxides (Ivanyuk et al., 2016; Krolop et al., 2019, 2022; Mitrofanova et al., 2023). Apatite trace-element chemistry and morphology suggest phosphate phases may record complex crystallization and alteration, affecting flotation and thermal behavior (Childress, 2016; Huang & Beaudoin, 2019; La Cruz et al., 2019; Mao et al., 2016).

Conventional beneficiation often struggles to achieve high iron recovery while keeping phosphorus low. Magnetic separation efficiently recovers iron but may also extract composite particles with trapped apatite. Flotation can separate apatite or reject phosphorus-bearing minerals, but its efficiency relies on liberation, chemistry, oxidation, reagent selectivity, and fine particles (Birinci, 2021; Elbendary et al., 2019; Ruan et al., 2019; Silva et al., 2020). In steelmaking, phosphorus is problematic as even low levels can reduce quality and increase costs. Thus, phosphorus removal must consider mineralogy, chemistry, and process integration, not just single steps (Ofoegbu, 2019; Pereira & Papini, 2015).

Roasting-assisted beneficiation is gaining attention because thermal treatment can modify iron-phase stability, magnetic susceptibility, apatite–magnetite interfaces, and particle friability, thereby improving separation. Techniques such as microwave-assisted thermal treatment, magnetization roasting, coal- and gas-based reduction, and additive- and sodium-assisted processes have been explored for high-phosphorus iron ores (Cai et al., 2018; Chen et al., 2024a; Han et al., 2017; Pan et al., 2022; Wu et al., 2021, 2023). However, roasting isn't always beneficial; excessive heat may cause sintering, formation of metallic iron, phosphorus redistribution, secondary phosphates, or slag phases, reducing concentrate quality despite higher iron recovery (Hu et al., 2025a-c; Ji et al., 2024a, 2024b; Tang et al., 2016).

Recent studies increasingly suggest that selective moderate-temperature reduction may offer a broader operating window than aggressive high-temperature reduction. Rather than maximizing metallic iron formation, moderate reduction aims to partially magnetize iron phases while preserving apatite stability and limiting phosphorus transfer into metallic iron. This concept has been explored in coal-based, CO-based, hydrogen-rich, and additive-modified systems (Chen, Liu, & Zuo, 2022; Suleimen et al., 2024, 2025a, 2025b; Wu et al., 2026; Xu et al., 2025). Nevertheless, the relationships among oxygen potential, degree of reduction, mineral texture, phosphorus migration, flotation response, and industrial scale-up remain insufficiently established.

This review evaluates roasting-assisted beneficiation of magnetite–apatite and related phosphorus-bearing iron ores. It covers mineralogy, thermodynamics, reduction kinetics, phosphorus partition, liberation, flotation, hydrometallurgy, dry beneficiation, industrial use, and sustainability. The key idea is that beneficiation depends on a coupled sequence: mineral texture influences thermal response; oxygen potential affects phase change; reduction degree controls phosphorus partitioning; microfracturing aids liberation; and surface chemistry guides separation (Liu et al., 2017; Chen & Zuo, 2022).

2. METHODOLOGY

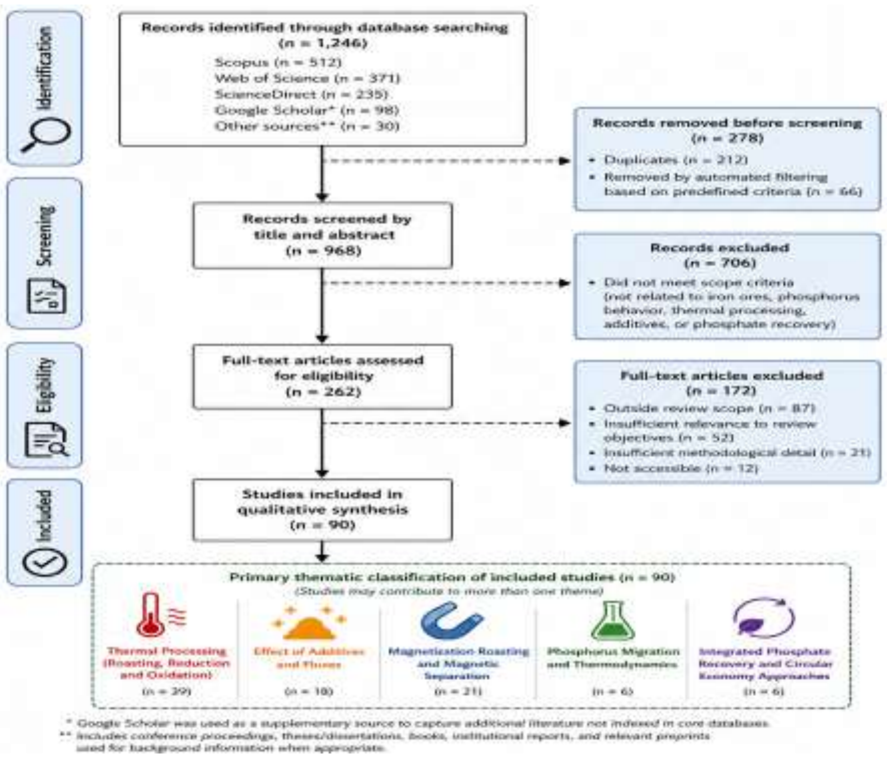
This review adopted a PRISMA-informed methodology adapted from the PRISMA 2020 framework proposed by Page et al. (2021). The manuscript should be interpreted as a critical review rather than a fully systematic review because its objective extends beyond cataloging the literature toward mechanistic integration and critical interpretation of roasting-assisted beneficiation behavior.

The bibliographic survey included peer-reviewed journal articles, conference papers with substantial technical relevance, book chapters, mineral processing studies, thermodynamic investigations, flotation studies, industrial beneficiation reports, and selected theses with unique data. The main databases were Scopus, Web of Science, ScienceDirect, SpringerLink, Wiley Online Library, MDPI, ACS Publications, Google Scholar, publisher websites, and academic repositories.

The search strategy combined terms associated with magnetite–apatite ores, iron oxide–apatite deposits, Kiruna-type deposits, roasting beneficiation, magnetization roasting, oxidizing roasting, direct reduction, selective reduction, phosphorus removal, apatite flotation, phosphate recovery, hydrogen reduction, alkaline leaching, acid leaching, dry beneficiation, and phosphorus partition. Earlier references were retained when necessary for deposit geology, apatite trace-element interpretation, beneficiation fundamentals, or phosphorus removal mechanisms (Childress, 2016; Mondal, 2017; Pereira & Papini, 2015).

Excluded studies lacking experimental detail, roasting atmosphere, mineralogy, or phosphorus data unless they offered mechanistic insight into surface chemistry, dry separation, or pyrometallurgy, with some broader flotation and beneficiation studies retained (Derqaoui et al., 2022; Faris, 2024; Faris et al., 2017; Jafari et al., 2018; Sedlmaier Costa Coelho et al., 2025).

A structured review followed PRISMA 2020 to evaluate studies on roasting-assisted beneficiation of magnetite–apatite and phosphorus-rich iron ores, focusing on thermal processing, phosphorus behavior, phase changes, magnetic separation, additives, and recovery strategies. Most studies emphasized magnetization roasting and magnetic separation, with fewer covering phosphorus migration, mild reduction, or recovery. The study selection workflow is shown in Figure 1.



* Google Scholar was used as a supplementary source to capture additional literature not indexed in core databases.
** Includes conference proceedings, theses/dissertations, books, institutional reports, and relevant preprints used for background information when appropriate.

Figure 1. PRISMA-informed workflow used for identification, screening, eligibility evaluation, and selection of references included in this critical review. Adapted from Page et al. (2021).

Figure 1 shows that the literature search initially identified 1,246 records from major scientific databases and supplementary sources. After duplicate removal and automated filtering based on predefined criteria, 968 records remained for title and abstract screening. The subsequent eligibility assessment resulted in the selection of 90 studies for qualitative synthesis. The progressive reduction in the number of records reflects the application of relevance, methodological quality, and accessibility criteria designed to ensure that the final dataset was directly aligned with the review's objectives.

The thematic classification of the included studies highlights the dominant research directions in the field. Most investigations focused on thermal processing phenomena, including roasting, reduction, and oxidation behavior, followed by magnetization roasting and magnetic separation. In contrast, relatively few studies specifically addressed phosphorus migration, thermodynamic behavior, and integrated phosphate recovery strategies. This imbalance indicates that substantial knowledge has been generated regarding iron-phase transformation and magnetic upgrading, whereas phosphorus redistribution mechanisms and phosphate valorization pathways remain comparatively underexplored.

The results summarized in Figure 1 also reveal an important shift in recent research trends. While conventional studies largely emphasized maximizing iron recovery through aggressive thermal treatment and magnetic separation, more recent investigations have increasingly examined selective reduction, phosphorus control, additive-assisted roasting, and integrated resource-recovery approaches. These emerging themes form the conceptual foundation for the present review and motivate the critical evaluation of roasting conditions, phosphorus partitioning mechanisms, liberation behavior, and sustainable beneficiation strategies discussed in the following sections.

The literature on roasting-assisted beneficiation of magnetite–apatite ores encompasses a broad spectrum of studies, ranging from laboratory-scale experiments and thermodynamic simulations to pilot-scale investigations, industrial case studies, review articles, and academic theses. Although each category contributes valuable information, the strength and applicability of the resulting evidence vary considerably according to experimental scale, technological maturity, operational realism, and degree of validation.

Consequently, interpretation of beneficiation performance should not rely exclusively on the number of published studies but also on the nature of the evidence supporting the reported findings. Laboratory investigations primarily provide mechanistic understanding of phase transformations, phosphorus migration, liberation behavior, and flotation response, whereas pilot-scale and industrial studies offer critical insights into process stability, scalability, energy demand, and operational feasibility. To provide a structured assessment of the available knowledge base,

Table *1* classifies the studies included in this review according to study type, typical scale, technological maturity level (TRL), principal contribution, and inherent limitations.

Table 1 Classification of the evidence base according to study type, scale, and technological maturity level (TRL). Adapted from Page et al. (2021) and modified for roasting-assisted beneficiation studies.

[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Laboratory experimental	Bench scale	2–4	54	Mechanistic understanding	Limited scale representativeness
Pilot-scale studies	Pilot plant	4–6	11	Process validation	Limited operational duration
Industrial case studies	Commercial operations	7–9	5	Real process performance	Often limited data disclosure
Modeling and simulation	Computational	2–5	9	Process prediction	Strong dependence on assumptions
Review papers	Secondary evidence	N/A	8	Knowledge integration	No original experimental data
Theses and dissertations	Variable	2–5	3	Unique datasets	Limited peer review

To improve evidentiary consistency, the selected studies were additionally classified according to study type, technological maturity level (TRL), and degree of industrial validation. The literature was grouped into six categories: laboratory experimental studies, pilot-scale investigations, industrial case studies, modeling and simulation studies, review articles, and theses or dissertations.

Because beneficiation depends on scale phenomena like heat transfer, gas distribution, residence time, particle segregation, and process control, pilot and industrial studies were essential for evaluating roasting-assisted beneficiation. Laboratory studies clarified mechanisms such as phase transformations, phosphorus migration, flotation, and liberation.

The evidence reflects a field where most studies are laboratory-scale, with few pilot or industrial projects. Therefore, conclusions about industrial use, especially for emerging ideas like selective mild reduction and phosphate recovery, should be cautious.

3. MINERALOGICAL CHARACTERISTICS OF MAGNETITE–APATITE ORES

3.1. Deposit Types and Mineralogical Variability

Magnetite–apatite ores occur in several geological environments and display strong variability in mineralogy, texture, alteration intensity, and phosphorus distribution. Kiruna-type systems, El Laco-type deposits, Bafq district deposits, Sri Lankan magnetite–apatite mineralization, Kovdor apatite–magnetite ores, and Tomtor-related apatite–magnetite systems illustrate the broad mineralogical diversity of this ore family (Baranov & Tolstov, 2026; Ghazi et al., 2019; He et al., 2018; Heidarian et al., 2016; Ivanyuk et al., 2016; Nie et al., 2017; Tornos et al., 2017).

Kiruna-type deposits contain magnetite linked with fluorapatite, actinolite, feldspar, pyroxenes, amphiboles, and silicate gangue. Their origin may involve magmatic crystallization, magmatic-hydrothermal processes, melt immiscibility, or hydrothermal replacement. This genetic variability impacts magnetite chemistry and apatite morphology, affecting beneficiation response (Broughm et al., 2017; Huang & Beaudoin, 2019; Pietruszka et al., 2023; Rodríguez-Mustafa et al., 2020; Tornos et al., 2021, 2024).

Kola Peninsula and Kovdor-type ores demonstrate how spatial distribution of apatite and magnetite may vary within the same deposit. In some domains, apatite occurs as relatively coarse grains suitable for flotation after grinding. In others, it occurs as fine inclusions within magnetite or as complex intergrowths that generate composite particles after comminution (Ivanyuk et al., 2016; Krolop et al., 2019, 2022; Mitrofanova et al., 2023).

Hydrothermal overprinting complicates beneficiation by causing secondary phosphate phases, altering apatite chemistry, and changing interfacial bonding between iron oxides and gangue minerals. Studies indicate that apatite composition reflects variations in fluid chemistry, volatile content, and crystallization conditions (Chen, Lan, et al., 2023; Childress, 2016; La Cruz et al., 2019; Mao et al., 2016; Salazar et al., 2024). These changes affect roasting since altered apatite or secondary phases may react differently from primary fluorapatite.

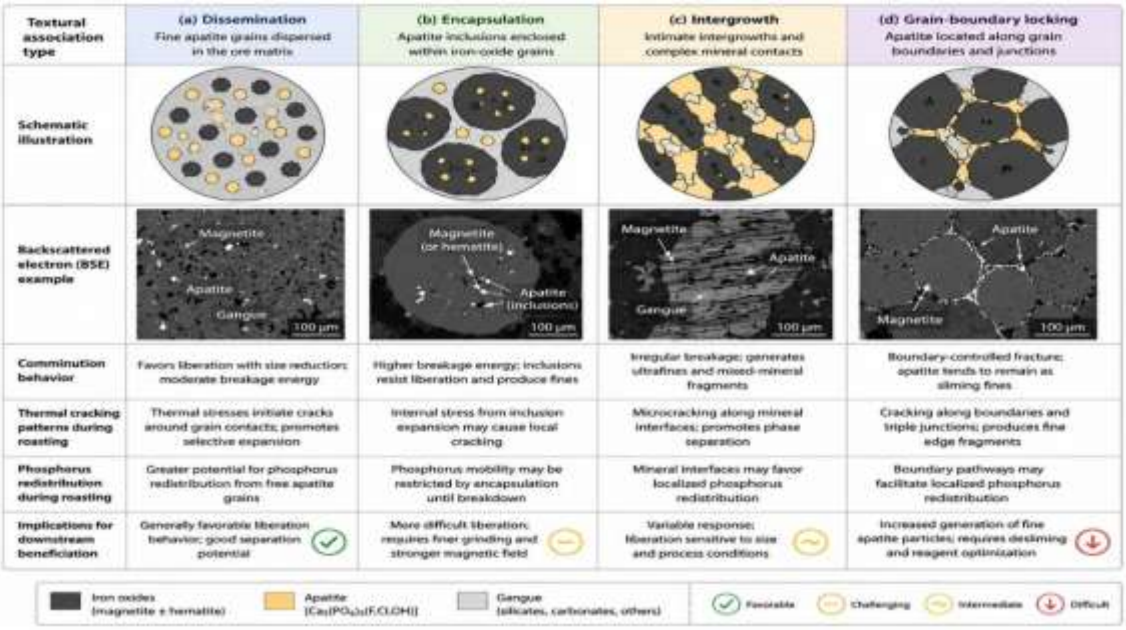
3.2. Mineral Phases, Textures, and Liberation Constraints

Magnetite and apatite are the main phases in most systems, but hematite, quartz, feldspar, amphiboles, pyroxenes, carbonates, sulfides, dolomite, calcite, and secondary phosphates may also be present depending on deposit type and alteration. The beneficiation response depends on bulk chemistry, mineral associations, and particle texture.

Apatite appears as grains, interstitial aggregates, fracture fillings, inclusions, or grain-boundary intergrowths, each with different implications. Disseminated apatite can be recovered by flotation after grinding, while encapsulated apatite may remain trapped in iron oxides. Grain-boundary apatite may crack with thermal stress during heating and cooling (Cai et al., 2018; Krolop et al., 2022; Lu et al., 2024).

Process mineralogy studies indicate that liberation problems become particularly severe when apatite inclusions occur at the micron scale. In such cases, additional grinding may increase slime generation without sufficient liberation. This limitation explains why flotation alone may be ineffective for some iron ore tailings or apatite-bearing iron concentrates (Birinci, 2021; Rajabi & Pourghahramani, 2025).

Phosphorus in magnetite–apatite ores depends on grade and textures between apatite, iron oxides, and gangue minerals. These textures affect liberation, comminution, phosphorus redistribution during thermal treatment, and beneficiation. Depending on whether apatite occurs as disseminated grains, inclusions, intergrown phases, or boundary networks, responses to grinding, roasting, magnetic separation, and flotation vary. Figure 2 summarizes these textures and their effects on liberation and roasting-based beneficiation.



Textural association type	(a) Dissemination Fine apatite grains dispersed in the ore matrix	(b) Encapsulation Apatite inclusions enclosed within iron-oxide grains	(c) Intergrowth Intimate intergrowths and complex mineral contacts	(d) Grain-boundary locking Apatite located along grain boundaries and junctions
Schematic illustration				
Backscattered electron (BSE) example				
Comminution behavior	Favors liberation with size reduction; moderate breakage energy	Higher breakage energy; inclusions resist liberation and produce fines	Irregular breakage; generates ultrafines and mixed-mineral fragments	Boundary-controlled fracture; apatite tends to remain as sliming fines
Thermal cracking patterns during roasting	Thermal stresses initiate cracks around grain contacts; promotes selective expansion	Internal stress from inclusion expansion may cause local cracking	Microcracking along mineral interfaces; promotes phase separation	Cracking along boundaries and triple junctions; produces fine edge fragments
Phosphorus redistribution during roasting	Greater potential for phosphorus redistribution from free apatite grains	Phosphorus mobility may be restricted by encapsulation until breakdown	Mineral interfaces may favor localized phosphorus redistribution	Boundary pathways may facilitate localized phosphorus redistribution
Implications for downstream beneficiation	Generally favorable liberation behavior; good separation potential ✓	More difficult liberation; requires finer grinding and stronger magnetic field ⊖	Variable response; liberation sensitive to size and process conditions ~	Increased generation of fine apatite particles; requires desliming and reagent optimization ↓

Figure 2. Schematic representation of magnetite–apatite textural associations, including dissemination, encapsulation, intergrowth, fracture filling, and grain-boundary locking. Adapted from Krolop et al. (2019), Childress (2016), La Cruz et al. (2019), and Tornos et al. (2024).

Figure 2 shows mineral texture mainly controls liberation and phosphorus behavior. Disseminated apatite is easiest to benefit from, as it can be liberated through standard crushing, and thermal treatment can improve separation by causing localized cracking. Encapsulated apatite, however, is harder to liberate because it stays enclosed within iron-oxide grains, needing finer grinding and producing more fines.

Intergrown textures are an intermediate, variable state characterized by irregular breakage, mixed minerals, and heterogeneous liberation, influenced by microcracks and mineral-contact weakening. Process optimization must consider mineralogy and particle size.

Grain-boundary locking creates beneficiation challenges, notably apatite along boundaries and junctions, which produce fine particles during grinding and redistribute phosphorus during thermal treatment. Overcoming this needs strategies like roasting, desliming, magnetic separation, flotation, or hydrometallurgy. Ultimately, Figure 2 shows roasting-assisted beneficiation effectiveness depends more on mineralogy and texture than phosphorus grade.

Magnetite–apatite ores' response to thermal treatment varies with ore genesis, phosphorus distribution, mineral associations, and texture. Phosphorus minerals, mainly apatite, range from coarse crystals to fine disseminations, impacting mineral liberation, phosphorus mobility during roasting, and beneficiation. Table 2 summarizes geological systems hosting these ores and their textural features affecting processing.

Table 2. Mineralogical and textural characteristics of representative magnetite–apatite systems and their implications for roasting-assisted beneficiation. Adapted from Ivanyuk et al. (2016), Krolop et al. (2019, 2022), Tornos et al. (2017), Huang and Beaudoin (2019), and Pietruszka et al. (2023).

[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Kiruna-type ores	0.3–1.0	Disseminated/intergrown apatite	Grain-boundary locking	Selective cracking required	Broughm et al. (2017); Tornos et al. (2017)
Kovdor/Kola systems	0.5–1.5	Fine apatite dissemination	Composite particles	Moderate thermal activation favorable	Ivanyuk et al. (2016); Mitrofanova et al. (2023)
El Laco-type systems	0.2–0.8	Massive/interstitial apatite	Variable liberation	Heterogeneous response	Tornos et al. (2017, 2021)
Hydrothermal overprinted ores	0.5–2.0	Secondary phosphates	Multi-phase phosphorus occurrence	Increased migration risk	La Cruz et al. (2019); Salazar et al. (2024)
Oolitic high-P iron ores	0.5–2.0	Fine P-bearing lamellae/inclusions	Severe locking	Reduction and leaching often required	Han et al. (2017); Wu et al. (2023); Xu et al. (2025)

Table 2 demonstrates that phosphorus content alone is not sufficient to predict beneficiation performance. Instead, the spatial distribution of phosphorus-bearing phases and their textural relationships with iron minerals exert a stronger influence on liberation efficiency and roasting behavior. Deposits containing coarse or interstitial apatite commonly exhibit more favorable liberation characteristics, whereas finely disseminated apatite, phosphorus-rich inclusions, and secondary phosphate assemblages frequently require additional thermal activation or chemical treatment to achieve adequate separation.

The table also highlights the importance of deposit-specific process design. Kiruna-type and Kovdor–Kola ores generally benefit from controlled thermal activation that promotes interfacial weakening and selective cracking, thereby improving liberation during subsequent grinding. In contrast, hydrothermally altered ores often contain phosphorus distributed among multiple mineral phases, increasing the complexity of phosphorus redistribution and potentially reducing beneficiation selectivity during roasting.

Oolitic high-phosphorus iron ores are challenging because phosphorus exists as fine lamellae, inclusions, or intergrowths within iron phases. Thermal treatment alone often fails to sufficiently reject phosphorus, necessitating combined methods such as reduction roasting, magnetic separation, flotation, or hydrometallurgy. Effectiveness depends more on ore texture and mineralogy than phosphorus grade.

4. THERMODYNAMICS AND KINETICS OF ROASTING-ASSISTED PROCESSING

4.1. Thermodynamic Framework for Iron Reduction and Phosphorus Stability

The effectiveness of roasting-assisted beneficiation depends on thermodynamic factors governing iron oxides, phosphate minerals, and phosphorus products. While temperature is often considered key, phase changes are primarily influenced by oxygen potential, gas composition, reductant activity, residence time, and mineral assemblage (Chen & Wu, 2024; Hu et al., 2025a).

The Fe–O system underpins iron phase changes during roasting. As oxygen partial pressure drops, iron oxides shift through hematite (Fe_2O_3), magnetite (Fe_3O_4), wüstite (FeO), and metallic iron (Fe). Phase boundaries depend on temperature and oxygen levels, indicating that roasting temperature alone doesn't fully capture reduction (Pan et al., 2022; Wu et al., 2021, 2023c).

Figure 3 highlights that beneficiation depends on the stability domains of iron phases. Selectively producing magnetite is preferred as it boosts magnetic susceptibility without significantly transferring phosphorus into metallic iron.

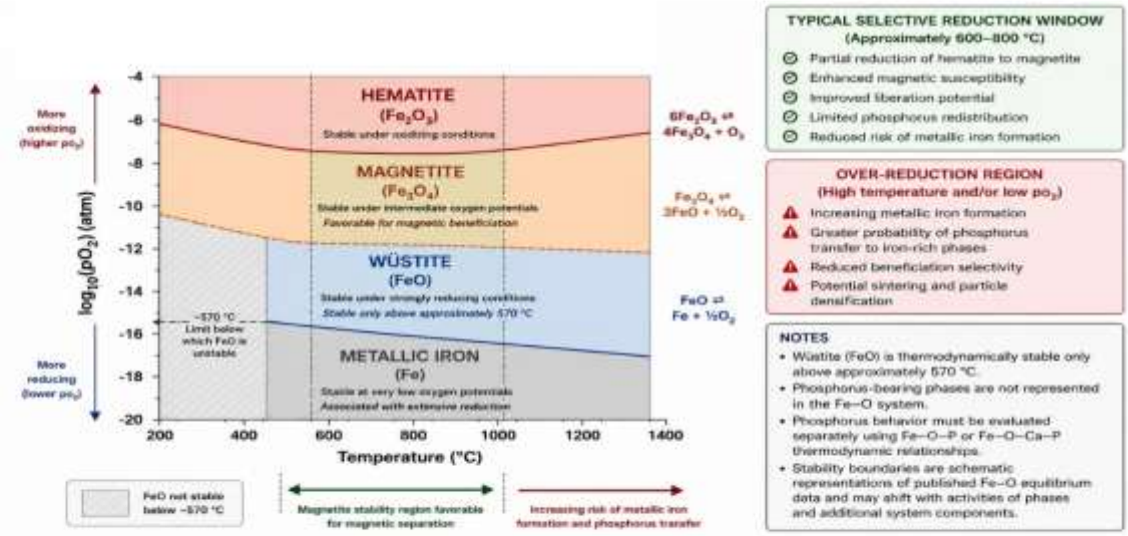


Figure 3. Fe–O phase stability diagram showing the thermodynamic domains of hematite, magnetite, wüstite, and metallic iron as functions of temperature and oxygen potential. The diagram was developed by the authors based on published studies of iron-oxide reduction and Fe–O phase equilibria. Adapted from (Chen et al., 2024b; Freindl et al., 2020; Cavaliere, 2022; Zhang et al., 2022; Xu et al., 2025).

Figure 3 demonstrates that the transition from magnetite to metallic iron occurs only under increasingly reducing conditions. This distinction is critical because the thermodynamic window that maximizes magnetic enhancement is not necessarily identical to the window that maximizes phosphorus rejection. Consequently, beneficiation optimization requires simultaneous consideration of both iron reduction and phosphorus stability.

At moderate oxygen potentials, phosphorus tends to remain associated with apatite or calcium phosphate phases. As pO_2 decreases and metallic iron becomes thermodynamically stable, phosphorus increasingly partitions into metallic iron, Fe–P alloys, or secondary phosphide phases (Hu et al., 2025c; Ji et al., 2024a, 2024b).

4.2. Influence of Gas Atmosphere and Oxygen Potential

Gas composition exerts a decisive influence on reduction behavior because the oxygen potential is directly governed by equilibrium relationships in the $CO–CO_2$ and $H_2–H_2O$ gas systems. Increasing the CO/CO_2 or H_2/H_2O ratio decreases oxygen potential and promotes progressive reduction from hematite to magnetite, wüstite, and ultimately metallic iron (Tang et al., 2016; Wu et al., 2023).

Ellingham-type thermodynamic relationships provide a useful framework for interpreting these effects. At a given temperature, higher reducing-gas activity increases the driving force for oxygen removal from iron oxides. Consequently, atmospheres rich in CO or H_2 accelerate reduction and increase metallization, whereas lower gas ratios favor partial reduction and selective magnetization (Cavaliere, 2022; Chen et al., 2023a).

Figure 4 is important to recognize that gas composition affects not only iron reduction but also phosphorus partitioning. Excessively reducing conditions may enhance iron recovery while simultaneously increasing phosphorus incorporation into metallic phases.

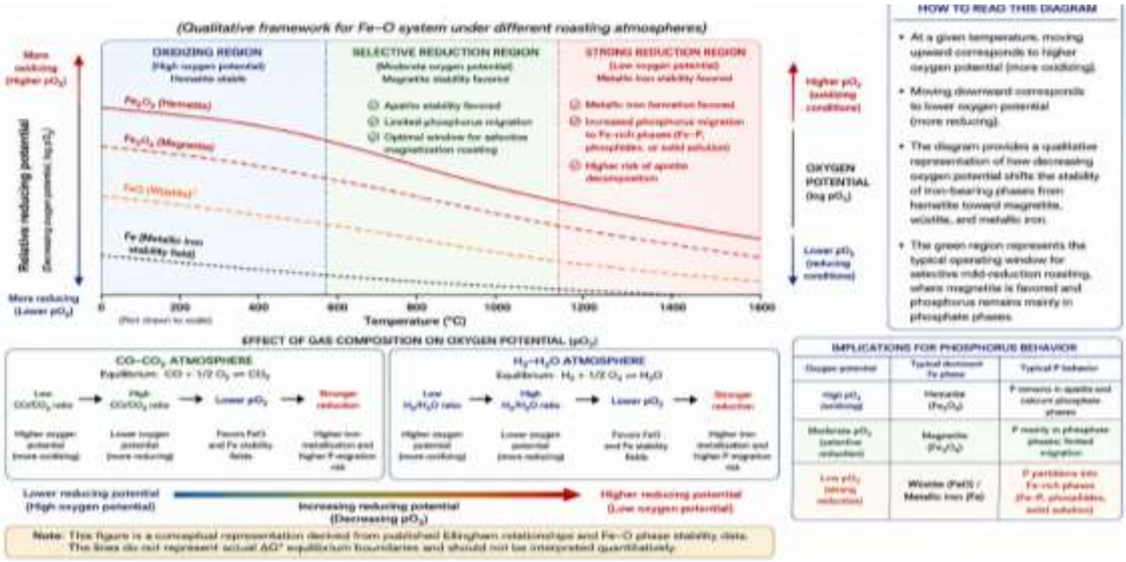


Figure 4. Conceptual Ellingham-based interpretation of reduction potential in CO–CO_2 and H_2–H_2O atmospheres during roasting-assisted beneficiation. Adapted from Cavaliere (2022), Chen et al. (2019), and Freindl et al. (2020).

Figure 4 illustrates that increasingly reducing atmospheres shift the equilibrium toward the formation of metallic iron. While this may improve iron recovery, it may also increase phosphorus migration into iron-rich phases, thereby reducing beneficiation selectivity. This trade-off forms the thermodynamic basis for selective mild-reduction strategies.

The thermodynamic behavior of phosphorus-bearing iron ores is controlled by a combination of temperature, oxygen potential, gas composition, residence time, and chemical additives. Although roasting temperature is frequently reported as the primary operating variable, beneficiation performance ultimately depends on the interactions among these parameters and their influence on phase stability, reduction intensity, and phosphorus partitioning.

Table *3* summarizes the principal thermodynamic variables governing iron oxide reduction and phosphorus behavior during roasting-assisted beneficiation.

Table 3. Main thermodynamic variables controlling iron reduction and phosphorus partition during roasting-assisted beneficiation. Adapted from Cavaliere (2022), Chen et al. (2024b), Freindl et al. (2020), Han et al. (2017), Wu et al. (2023), and Xu et al. (2025).

Temperature	Increases reduction extent	Positive	Variable
Oxygen potential (pO_2)	Controls phase stability	Strong	Strong
CO/CO_2 ratio	Controls reducing potential	Positive	Often negative
H_2/H_2O ratio	Controls reducing potential	Positive	Variable
Residence time	Approaches equilibrium	Positive	Variable
Additives	Modify phosphate stability	Variable	Positive

Table 3 demonstrates that oxygen potential is one of the most influential variables governing both iron recovery and phosphorus selectivity. While increasing reduction intensity generally favors iron oxide reduction and magnetic enhancement, excessively reducing conditions may promote phosphorus transfer into metallic iron, Fe–P alloys, or secondary phosphide phases. Consequently, the thermodynamic conditions that maximize iron recovery are not necessarily those that maximize phosphorus rejection.

The table also highlights the critical role of gas composition. Increasing CO/CO_2 or H_2/H_2O ratios lowers oxygen potential and shifts equilibrium toward deeper reduction. Although such conditions may improve metallization and iron recovery, they can simultaneously decrease beneficiation selectivity by increasing phosphorus migration into iron-rich phases. This thermodynamic trade-off provides the scientific basis for selective mild-reduction strategies.

Residence time and additive chemistry further influence beneficiation behavior by modifying the extent of reaction and the stability of phosphorus-bearing phases. Additives such as sodium-containing compounds or calcium-bearing materials may alter phosphate stability, modify gangue reactions, and improve phosphorus fixation under specific operating conditions. Overall, the optimum roasting window results from balancing iron reduction, phosphorus control, energy consumption, and downstream separation requirements, rather than maximizing the extent of reduction alone.

These thermodynamic considerations provide the foundation for understanding the different roasting routes discussed in the following sections, including oxidizing roasting, magnetization roasting, and selective moderate-temperature reduction.

4.3. Kinetics of Reduction and Phase Transformation

Roasting kinetics influence beneficiation selectivity because reduction behavior depends not only on equilibrium stability but also on gas diffusion, heat transfer, nucleation, particle size, and residence time. Reduction often proceeds through a heterogeneous or shrinking-core pattern, in which external layers reduce more rapidly than internal regions (Chen, Liu, Chen, & Zuo, 2022).

Fine particles generally reduce faster because diffusion distances are shorter. Coarse particles may develop partially oxidized cores surrounded by reduced external layers. Such heterogeneity complicates magnetic separation because composite particles may exhibit variable magnetic susceptibility and variable phosphorus content. Reduction heterogeneity is also relevant for hydrogen-based mineral phase transformation and grinding behavior (Freindl et al., 2020; Tian et al., 2026).

Temperature accelerates reduction, but higher temperatures (above 800–950 °C) can lead to unwanted effects such as metallic iron formation, phosphorus migration, and sintering. Studies show increased magnetization boosts iron recovery but lowers dephosphorization efficiency (Ji et al., 2024b; Suleimen et al., 2025a; Wang et al., 2026; Wu et al., 2026).

Residence time is equally important. Insufficient thermal exposure may produce incomplete magnetization, whereas excessive residence time may intensify phosphorus redistribution, grain growth, or sintering. Multi-stage dynamic magnetizing roasting was proposed, in part, to manage these competing kinetic effects in oolitic hematite systems (Zhang et al., 2022).

4.4. Oxidizing Roasting, Magnetization Roasting, and Selective Reduction

Oxidizing roasting promotes magnetite-to-hematite transformation, expansion, and cracking, but excessive temperature causes coalescence and densification, reducing liberation. Magnetic separation of hematitic ores requires optimizing thermal conditions to prevent sintering and maintain efficiency (Neuppmann & da Luz, 2022).

Magnetization roasting turns weakly magnetic iron phases into magnetite, enhancing magnetic response and iron recovery. It's well-studied for refractory high-phosphorus iron ores and oolitic systems (Pan et al., 2022; Xiao & Zhou, 2019; Zhang et al., 2022). However, it doesn't remove phosphorus on its own; it must be combined with flotation, leaching, or additives to keep phosphorus locked or redistributed. Moderate-temperature reduction (650-800 °C) balances magnetization and phosphorus control, keeping phosphorus bound to apatite or phosphate phases instead of diffusing into iron (Han et al., 2017; Suleimen et al., 2024; Wu et al., 2023; Xu et al., 2025).

High-temperature reduction and smelting systems operate above approximately 1000–1100 °C and aim to maximize metallization. These routes may yield elevated iron recovery but often reduce phosphorus selectivity, as phosphorus partitions into metallic iron, slag, or Fe–P alloy phases (Hu et al., 2025c; She et al., 2017; Tang et al., 2016).

Conventional reduction roasting maximizes iron metallization through severe thermal and reducing conditions, but over-reduction causes phosphorus redistribution, apatite destabilization, metallic iron formation, and Fe–P associations that hinder beneficiation. Recently, focus shifted to selective mild-reduction strategies that emphasize controlled phase changes over maximum reduction. Under these conditions, partial conversion of hematite to magnetite improves magnetic response, keeps apatite stable, and limits phosphorus mobility (Chen, Liu, & Zuo, 2022). Figure 5 shows this process and its impact on mineralogy, phosphorus behavior, and liberation.

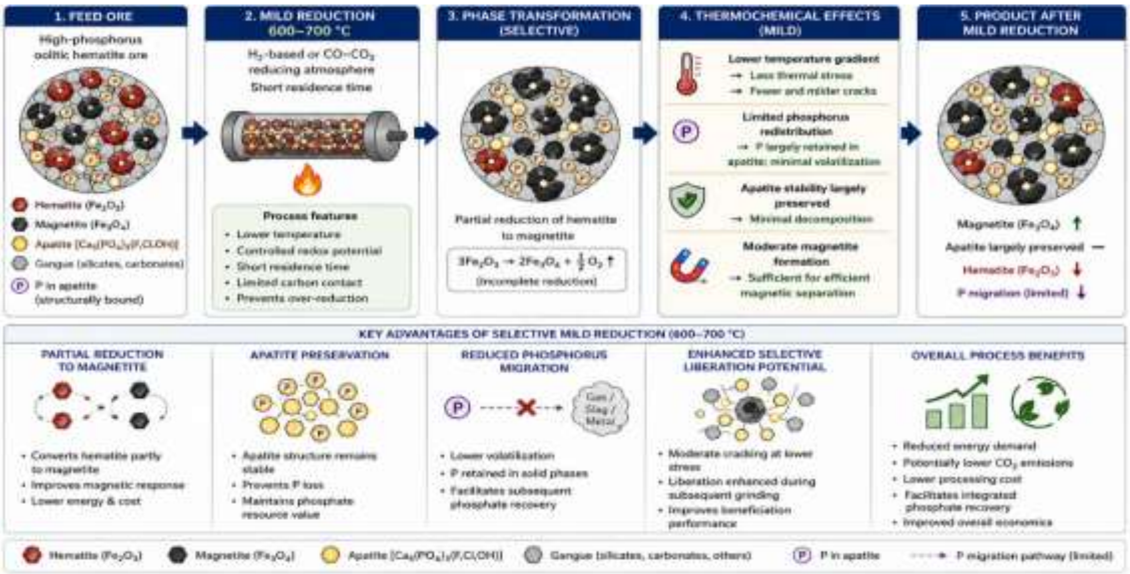


Figure 5. Conceptual representation of selective moderate-temperature reduction emphasizing partial magnetization, apatite preservation, controlled oxygen potential, and limited phosphorus migration. Adapted from Han et al. (2017), Ji et al. (2024a, 2024b), Suleimen et al. (2024), and Wu et al. (2023).

Figure 5 illustrates the fundamental principle of selective mild reduction, in which the objective is not the complete reduction of iron oxides but rather controlled mineralogical modification within a restricted temperature window. Under moderately reducing conditions, hematite is partially converted to magnetite, thereby improving magnetic properties while avoiding extensive formation of metallic iron. This approach minimizes the risk of phosphorus transfer into iron-rich phases and preserves the potential for subsequent selective separation.

The figure also highlights the importance of maintaining apatite stability during thermal treatment. Compared with more aggressive reduction routes, mild reduction generally limits phosphorus redistribution and reduces the likelihood of phosphorus incorporation into metallic iron or secondary reaction products. As a result, phosphorus remains predominantly associated with phosphate-bearing phases, preserving opportunities for downstream phosphate recovery and improving overall resource utilization (Freindl et al., 2020).

Another important aspect shown in Figure 5 is the relationship between controlled thermal activation and liberation behavior. Moderate thermochemical stresses can generate localized cracking and weakening of mineral associations without causing excessive sintering or over-reduction. These effects increase the probability of selective breakage during subsequent grinding stages, enhancing the separation of iron-bearing minerals from apatite and gangue phases.

From a process-design perspective, selective mild reduction represents a compromise between magnetic enhancement and phosphorus control. Rather than maximizing the extent of reduction, the strategy seeks to optimize phase transformation, liberation potential, and beneficiation selectivity while reducing energy consumption and minimizing undesirable phosphorus migration. This concept underpins several emerging beneficiation routes that integrate thermal activation, magnetic separation, and phosphate recovery into a more resource-efficient processing framework.

Thermal treatment strategies for phosphorus-bearing iron ores vary widely in reduction, phase transformation, phosphorus behavior, and beneficiation. The roasting conditions impact mineralogy, liberation, magnetic properties, and phosphorus partitioning. Various thermal routes are developed to optimize iron recovery, control phosphorus, and reduce energy use, while minimizing the formation of unwanted phases. Table 4 compares key thermal processes for high-phosphorus ores, detailing conditions, transformations, outcomes, and limitations.

Table 4. Comparative summary of roasting routes, thermodynamic behavior, and beneficiation implications. Adapted from Pan et al. (2022), Wu et al. (2021, 2023), Zhang et al. (2022), Suleimen et al. (2024), and Tang et al. (2016).

[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Oxidizing roasting	600–950	Air/O2	Magnetite to hematite	Moderate	Variable	Sintering risk
Magnetization roasting	700–950	CO/H2/coal	Hematite to magnetite	High	Moderate	P redistribution
Selective reduction	650–800	Weakly reducing	Partial magnetization	High	Higher	Atmosphere control
High-temperature reduction	>1000	Strongly reducing	Metallic iron formation	Very high	Low	Fe–P contamination
Additive-assisted roasting	650–1000	Variable	Modified phosphate stability	Variable	Variable	Reagent management

Table 4 highlights the strong dependence of beneficiation performance on the degree of reduction and the resulting behavior of phosphorus. Oxidizing roasting primarily modifies the mineralogy of iron oxides and may improve subsequent separation processes, although excessive temperatures can promote sintering and reduce liberation efficiency. Magnetization roasting remains one of the most widely investigated approaches because converting hematite to magnetite significantly enhances magnetic separation performance while maintaining relatively high iron recovery.

Selective temperature reduction to 650–800 °C is often seen as the best balance between iron recovery and phosphorus control. Controlled reduction can enhance magnetic response and liberation, while limiting phosphorus redistribution. This approach is useful for treating magnetite–apatite and other phosphorus-rich iron ores.

High-temperature reduction enhances iron recovery by forming metallic iron but increases phosphorus partitioning into iron, potentially harming concentrate quality. Additive-assisted roasting can help control phosphorus levels, but its success depends on additive selection, dosage, mineralogy, and process control. Ultimately, the best thermal route depends on balancing iron recovery, phosphorus management, energy use, and processing needs.

4.5. Thermodynamic Modeling Approaches

Thermodynamic modeling is vital for understanding phase changes, phosphorus redistribution, gas–solid reactions, and optimizing roasting during phosphorus-bearing iron ore beneficiation. Since direct experiments under industrial conditions are challenging, computational thermodynamics predicts equilibrium states, stability zones, and the effects of temperature, atmosphere, and additives on iron and phosphorus (Xu et al., 2025; Bichi et al., 2026).

FactSage is a widely used platform for calculating equilibrium phase assemblages, oxygen-potential diagrams, slag chemistry, phosphorus partitioning, and reduction pathways in iron-bearing systems. It combines Gibbs-energy minimization with extensive thermodynamic databases to predict phase stability in multicomponent systems containing elements such as Fe, O, P, Ca, Si, Mg, Al, and others in oolitic and magnetite–apatite ores. Studies on phosphorus redistribution during reduction roasting and smelting separation use FactSage to evaluate metallic iron, phosphates, iron phosphides, and slag phases under different oxygen potentials (Tang et al., 2016; She et al., 2017; Ji et al., 2024; Suleimen et al., 2025).

HSC Chemistry is widely used in mineral processing and extractive metallurgy for generating predominance diagrams, Ellingham diagrams, equilibrium calculations, reaction Gibbs energies, and phase equilibria. It is especially useful for evaluating phosphorus removal, roasting routes, hydrogen reduction, and strategies to maximize magnetite while limiting phosphorus transfer.

Predominance diagrams help identify oxygen-potential windows that favor magnetite stability and suppress metallization and phosphorus contamination.

Thermo-Calc has increasingly been used for complex metallurgical systems due to its CALPHAD methodology, allowing systematic evaluation of phase evolution over broad ranges. It is especially valuable for studying multiphase interactions and phase transitions. While its use in phosphorus-rich iron ore beneficiation is more limited than FactSage and HSC Chemistry, Thermo-Calc has significant potential for future thermodynamic and kinetic studies (Cavaliere, 2022; Xu et al., 2025).

Thermodynamic models are important but limited. They often ignore kinetic constraints, gas-diffusion issues, mineral heterogeneity, texture effects, and incomplete reactions. Thus, predictions serve as stability boundaries and process tendencies, not as exact measures of industrial performance. Reliable design combines thermodynamics with kinetic tests, mineralogy, and pilot studies (Chen et al., 2023b; Donskoi et al., 2022; Xu et al., 2025).

Thermodynamic modeling offers a powerful tool for understanding roasting, phase changes, phosphorus partitioning, and process optimization. Future studies should more effectively integrate thermodynamics, kinetics, mineralogy, machine learning, and digital twins to predict industrial beneficiation performance.

4.6. Scale Dependence of Reduction Thermodynamics

Although thermodynamic principles are independent of scale, the practical manifestation of reduction equilibria is strongly influenced by reactor design, heat-transfer characteristics, gas-flow patterns, residence time distribution, and mass-transfer limitations. Consequently, reduction behavior observed in laboratory experiments does not necessarily translate directly to pilot-scale or industrial systems (Xu et al., 2025; You et al., 2024).

Laboratory furnaces remain the most common platform for investigating roasting and reduction phenomena because they provide excellent control of temperature, atmosphere composition, and residence time. These systems have generated much of the current understanding of hematite-to-magnetite conversion, phosphorus migration, additive effects, and reduction kinetics (Chen et al., 2022b; Han et al., 2017; Ji et al., 2024). However, laboratory reactors typically employ small particle masses, uniform heating conditions, and idealized gas distributions, often producing reaction environments that are substantially more homogeneous than those encountered in industrial operations.

Rotary kilns add complexity with continuous solids movement, variable gas–solid contact, temperature gradients, and changing residence times. Industrial studies show reduction levels often differ from laboratory predictions due to heat transfer limits, particle segregation, local oxygen variations, and incomplete gas use (You et al., 2024; Wang et al., 2026). These effects are especially significant when selective reduction, not full metallization, is needed.

Shaft furnaces improve gas efficiency and counter-current contact. Hydrogen-based reduction boosts thermodynamics, enabling rapid reduction and affecting phosphorus behavior (Cavaliere, 2022; Chen et al., 2022a). However, temperature gradients, gas distribution, and pellet permeability affect equilibrium achievement.

Fluidized-bed reactors represent another important processing route because they provide excellent heat and mass transfer characteristics, high reaction rates, and relatively uniform temperature profiles. These systems are particularly attractive for hydrogen reduction and fine-particle processing. However, fluidization hydrodynamics, particle entrainment, agglomeration, and gas-channeling phenomena may substantially influence reduction pathways and phosphorus redistribution behavior (Faris et al., 2017; Cavaliere, 2022). Consequently, equilibrium calculations alone are often insufficient to predict industrial performance.

Scale effects are crucial when considering phosphorus migration and beneficiation goals. Lab studies often show favorable phosphorus partitioning under controlled conditions with short diffusion distances. In industry, larger particles, uneven temperatures, and nonuniform reduction can create conditions that promote the transfer of phosphorus into metallic iron or secondary phosphate phases (Suleimen et al., 2024; Wu et al., 2023; Ji et al., 2024).

These observations highlight the need for caution when extrapolating laboratory-scale thermodynamic results to industrial applications. Successful scale-up requires integration of equilibrium calculations with kinetic modeling, transport phenomena, reactor engineering, and pilot-scale validation. Future developments should focus on coupling thermodynamic simulations with computational fluid dynamics (CFD), discrete-element modeling (DEM), and process mineralogy to better predict industrial reduction performance and phosphorus behavior across multiple processing scales.

5. PHOSPHORUS PARTITION AND MIGRATION MECHANISMS

Phosphorus partitioning in roasting-assisted beneficiation is challenging as thermal treatment can preserve apatite or increase phosphorus contamination in iron-rich products. Main mechanisms include solid-state diffusion, interfacial transfer, secondary phosphate formation, slag partition, gasification under special conditions, and incorporation into metallic iron.

Gas-based reduction studies show phosphorus migration depends on reduction degree and atmosphere composition. Under moderate reduction, phosphorus stays in apatite or phosphate-rich phases. Stronger reduction causes phosphorus to migrate to metallic iron or form secondary compounds, reducing dephosphorization efficiency (Ji et al., 2024b; Wu et al., 2023). Hydrogen-rich sintering studies reveal phosphorus behavior is sensitive to gas composition and mineral phase transformation (Chen, Liu, Chen, & Zuo, 2022; Chen, Liu, & Zuo, 2022).

Additive-assisted systems modify phosphorus behavior by altering reaction pathways. Sodium-based additives may improve dephosphorization and iron grain growth, while dephosphorization agents may change reaction behavior during direct reduction roasting (Chen & Wu, 2024; Hu et al., 2025a; Wu et al., 2021). Eggshell-derived calcium additions have also been studied as green dephosphorization agents and reduction accelerators (Wu et al., 2023c).

Leaching behavior after roasting provides additional evidence of phosphorus redistribution. Sulfuric acid roasting of phosphate-bearing minerals, alkaline leaching of refractory concentrates, acid leaching, and sequential chemical separation demonstrate that phosphorus extraction depends on phase form, accessibility, and gangue dissolution (Ali & Yassin, 2025; Bichi et al., 2026; Hu et al., 2025b; Sparrow et al., 2022).

Phosphorus behavior during thermal processing affects iron ore beneficiation, depending on temperature, oxygen, reduction, mineral associations, and slag chemistry. These factors determine if phosphorus stays with apatite, forms secondary phosphates, enters metallic iron, or goes into slag. Understanding these pathways helps improve iron recovery and phosphorus management. Figure 6 summarizes phosphorus partitioning during roasting, reduction, and smelting, and the factors influencing its migration and distribution.

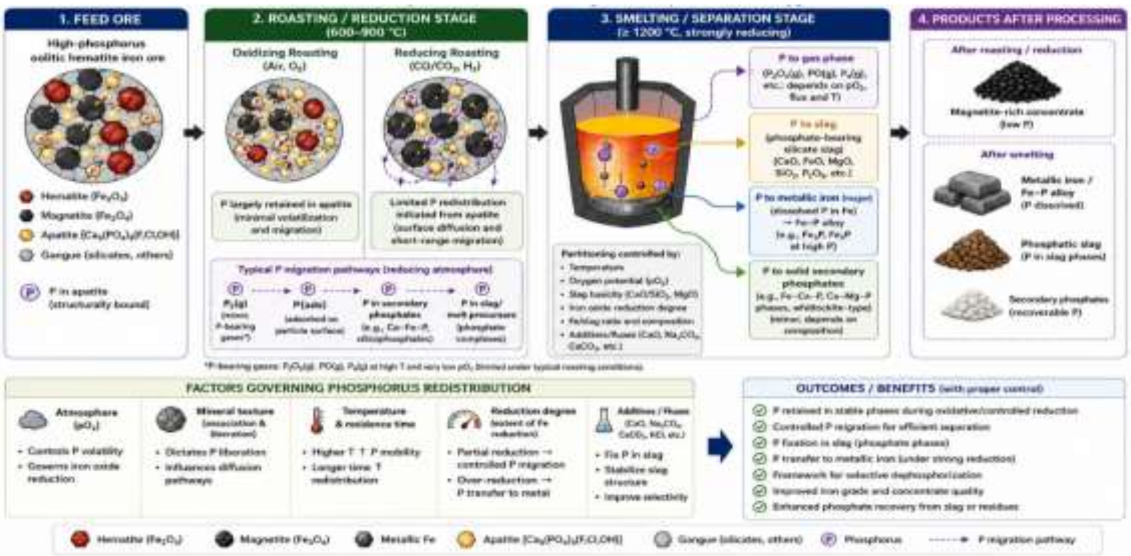


Figure 6. Schematic representation of phosphorus redistribution pathways during roasting-assisted beneficiation, including apatite preservation, metallic iron contamination, secondary phosphate formation, gas-related transformation, slag partition, and leaching-sensitive phases. Adapted from Wu et al. (2023), Ji et al. (2024b), Suleimen et al. (2025a), Bichi et al. (2026), and Chen, Liu, and Zuo (2022).

Figure 6 shows that phosphorus redistribution is dynamic, driven by evolving mineral phases and thermodynamic conditions during thermal treatment. During oxidizing roasting, phosphorus stays with apatite and phosphates, with little mobility or volatilization. In reduction, localized redistribution can occur via diffusion, surface migration, or secondary phosphates, influenced by temperature, time, and oxygen levels.

The figure shows phosphorus partitioning becomes more complex under reducing, high-temperature conditions. During smelting, phosphorus distributes among metallic iron, slag, secondary phosphates, and sometimes gaseous species. In ironmaking, phosphorus tends to dissolve in metallic iron under reducing conditions, whereas under oxidizing conditions, basic slags favor phosphorus in phosphate-bearing slag phases.

The final phosphorus distribution impacts beneficiation and metallurgy. Retaining phosphorus in apatite or recoverable phosphate phases enables selective recovery, whereas transfer to metallic iron can compromise product quality and requires dephosphorization. Effective management depends on controlling reduction, oxygen potential, slag chemistry, and residence time to direct phosphorus to the optimal phase for processing.

Phosphorus distribution during thermal processing depends on temperature, oxygen potential, and the reduction of iron oxides, thereby affecting the stability of hematite, magnetite, and metallic iron. These redox conditions influence how phosphorus partitions among apatite, secondary phosphates, metallic iron, and slag. Choosing proper roasting conditions is crucial for balancing iron recovery and phosphorus control. Table 5 summarizes how iron phases, phosphorus distribution, and operational outcomes evolve across various thermal regimes, as reported in the literature.

Table 5. Temperature-dependent phosphorus partition during roasting-assisted beneficiation. Adapted from Ji et al. (2024a, 2024b), Suleimen et al. (2025a, 2025b), Bichi et al. (2026), Tang et al. (2016), and Hu et al. (2025c)

500–650	Magnetite/hematite	Apatite/phosphate	Moderate	Favorable preservation
650–800	Magnetite	Apatite + limited redistribution	Weakly reducing	Balanced Fe recovery and P control
800–950	Magnetite + metallic Fe	Metallic Fe + secondary phosphates	Strongly reducing	Increased contamination
>1000	Metallic Fe/slag	Slag + Fe–P phases	Highly reducing	Reduced beneficiation selectivity

Table 5 shows changes in phosphorus behavior under thermal treatment from moderate to strongly reducing conditions. At low temperatures, phosphorus primarily remains in apatite and phosphate minerals, enabling selective recovery. Partial reduction of iron oxides can enhance magnetic properties while limiting phosphorus migration.

The temperature range of 650–800 °C is ideal because it promotes magnetite formation and retains phosphorus in apatite phases, improving magnetic separation without increasing phosphorus contamination. Studies suggest that a moderate temperature reduction enhances beneficiation while preserving phosphate recovery.

At higher temperatures and lower oxygen potentials, phosphorus partitions more into metallic iron and secondary phosphates. Fe–P associations and phosphorus slag compounds reduce the effectiveness of beneficiation and may increase phosphorus in iron concentrates. Excessive reduction risks compromising phosphorus selectivity and concentrate quality, highlighting the need to carefully control thermal treatment to balance iron recovery and phosphorus management.

6. THERMAL LIBERATION AND MICROSTRUCTURAL EVOLUTION

Thermal processing modifies liberation because roasting changes interfacial bonding strength, induces crack propagation, alters particle friability, and modifies mineral surface exposure. Differential thermal expansion between apatite and iron-bearing phases may generate localized stress accumulation during heating and cooling. Under moderate conditions, these stresses may weaken grain boundaries and improve liberation during subsequent grinding (Cai et al., 2018; Krolop et al., 2022).

6.1. Thermal Stress Generation and Crack Development

One of the primary mechanisms responsible for enhancing liberation during roasting is the generation of thermally induced stresses arising from differences in thermal expansion among mineral phases. Magnetite, hematite, apatite, silicates, and carbonate gangue minerals possess distinct coefficients of thermal expansion, elastic moduli, and thermal conductivities. Consequently, heating and cooling cycles produce localized strain incompatibilities at grain boundaries and mineral interfaces, generating internal stresses that may exceed the local fracture strength of the ore.

The magnitude of thermally induced stress can be approximated by the classical thermoelastic relationship:

$\sigma = E\alpha\Delta T$

where σ is the thermal stress, E is the elastic modulus, α is the coefficient of thermal expansion, and ΔT is the temperature variation experienced by the mineral particle. Although this simplified expression does not fully capture the heterogeneous stress field in polymineralic ores, it provides a useful framework for understanding the origin of thermally induced cracking.

In magnetite–apatite systems, thermal expansion mismatch is particularly important because apatite and iron oxides respond differently to temperature changes. During heating, differential expansion generates stress concentration zones at mineral contacts, while cooling may further intensify tensile stresses due to contraction mismatch. These stresses are commonly amplified by irregular grain geometry, crystallographic anisotropy, pre-existing defects, and heterogeneous mineral distributions (Cai et al., 2018; Krolop et al., 2022).

Once the local stress exceeds the fracture toughness of the mineral assemblage, crack nucleation may occur. Initial microcracks commonly develop at grain boundaries, triple junctions, inclusions, pores, and pre-existing defects. As roasting progresses, these cracks may propagate through mineral grains (transgranular cracking) or along interfaces (intergranular cracking), depending on mineral properties and stress distribution. Intergranular cracking is generally considered more favorable for beneficiation because it promotes selective liberation while minimizing excessive generation of ultrafine particles.

Crack propagation is also influenced by mineral phase transformations that occur during roasting. The conversion of hematite to magnetite, partial reduction to wüstite, defect generation, oxygen-vacancy formation, and localized volume changes may further increase internal strain energy and facilitate the development of interconnected fracture networks. Several studies have reported that controlled reduction roasting can significantly increase crack density and improve subsequent grinding performance by reducing the ore's mechanical strength and increasing its friability (Donskoi et al., 2022; Tian et al., 2026).

The effectiveness of thermal cracking is therefore governed by a complex interaction among temperature, heating rate, residence time, atmospheric composition, mineral texture, and degree of reduction. Moderate thermal treatment may generate sufficient microstructural damage to enhance liberation, whereas excessive temperatures may promote sintering, grain growth, crack healing, or partial melting, thereby reducing the benefits of thermal pretreatment. Consequently, optimal roasting conditions should be defined not only by the requirements of iron phase transformation but also by the extent and nature of thermally induced microstructural modification.

However, liberation enhancement is not universal. Excessive thermal exposure may promote sintering, localized melting, grain growth, densification, or partial crack closure. Ultrasonic treatment and alternative liberation studies on high-phosphorus iron ores show that physical weakening alone is insufficient if phosphorus remains chemically or texturally locked (Donskoi et al., 2022). Grinding characteristics after hydrogen-based phase transformation also demonstrate that phase evolution and mechanical breakage are coupled (Tian et al., 2026).

Roasting may reduce grinding energy demand by increasing friability, but excessive cracking may generate ultrafine slimes that reduce flotation selectivity through entrainment. This trade-off is especially important for apatite flotation from iron ore beneficiation tailings, where fine particles and tailings mineralogy already constrain recovery (Rajabi & Pourghahramani, 2025).

Mineral liberation is crucial for effective beneficiation of magnetite–apatite ores. Intergrowths between minerals and gangue hinder separation and increase grinding energy. Thermal processing alters mineral associations through cracking, expansion, and phase changes, promoting selective breakage and improved surface exposure. Figure 7 illustrates these mechanisms that enhance liberation and beneficiation.

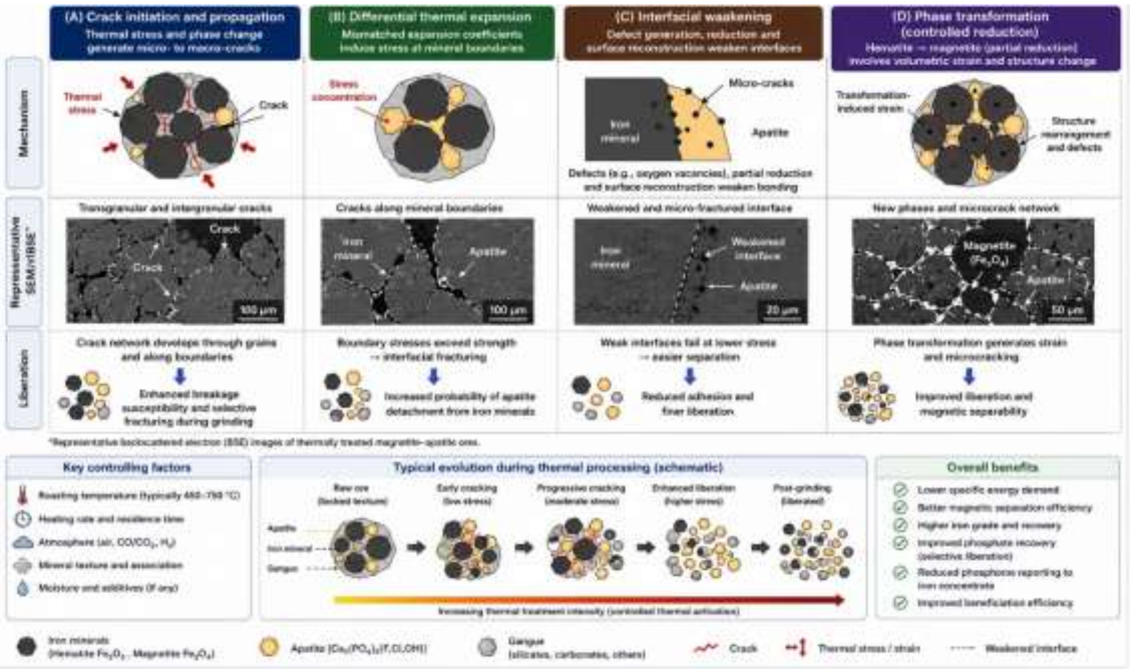


Figure 7. Mechanisms of liberation enhancement induced by thermal processing, including differential thermal expansion, crack propagation, interfacial weakening, friability increase, and potential sintering. Adapted from Cai et al. (2018), Donskoi et al. (2022), Krolop et al. (2022), and Tian et al. (2026).

Figure 7 shows that the enhancement of liberation during thermal processing results from multiple microstructural mechanisms rather than a single transformation. Thermal stresses from differential expansion cause cracks within grains and along grain boundaries, while heating promotes crack growth and the formation of interconnected fractures. These changes weaken the ore's mechanical integrity and increase its susceptibility to selective breakage during grinding.

The figure highlights how interfacial weakening between apatite and iron minerals affects mineral separation. Defects, iron oxide reduction, surface changes, and strain reduce bonding strength, aiding contact separation. This is especially important in fine, intergrown ores, where grinding struggles to liberate minerals without producing excessive fines.

Controlled phase transformation enhances liberation by inducing strain, microcracking, and structural changes during partial reduction of hematite to magnetite. This often improves magnetic separation, increases liberation, reduces grinding energy, and lowers phosphorus in concentrates. Thermal pretreatment thus serves as a microstructural engineering method to enhance comminution and beneficiation.

7. BENEFICIATION AFTER ROASTING

7.1. Magnetic Separation and Gravity-Assisted Separation

Magnetic separation is a key step after roasting. Thermal treatment boosts magnetic susceptibility by forming magnetite or metallic iron, improving recovery. Magnetization roasting with low-intensity magnetic separation is common for oolitic hematite and high-phosphorus iron ores (Pan et al., 2022; Xiao & Zhou, 2019; Zhang et al., 2022).

Nevertheless, elevated magnetic recovery does not necessarily correspond to low phosphorus contamination. If phosphorus migrates into metallic iron or remains in magnetic composite particles, magnetic separation may recover phosphorus together with iron. Direct reduction–magnetic separation studies confirm this trade-off (Hu et al., 2025a; Ji et al., 2024a; Wang et al., 2026; Wu et al., 2026).

Gravity and enhanced gravity separation may assist pre-concentration or recovery after reduction, particularly where density contrast is increased by thermal treatment. Comparisons of Falcon concentration and magnetic separation assisted by coal reduction show that combined physical routes may improve recovery but still require phosphorus control (Vapur et al., 2020).

7.2. Flotation of Phosphate Minerals

Flotation is central to phosphorus rejection and phosphate recovery after roasting. Thermal treatment modifies surface chemistry, oxidation state, roughness, liberation, and reagent adsorption. Studies on phosphate ore flotation show that reagent selectivity depends on apatite surface chemistry, collector structure, depressant chemistry, pH, dissolved ions, and pulp conditions (Derqaoui et al., 2022; Jafari et al., 2018; Liu et al., 2017; Ruan et al., 2018, 2019; Silva et al., 2020).

Sodium oleate and fatty-acid collectors remain widely applied for apatite flotation under alkaline conditions, but their selectivity may decrease when iron oxide surfaces are activated or when dissolved ions modify surface charge. Metal-ion effects, dolomite/apatite interactions, and collector concentration control demonstrate that flotation selectivity cannot be predicted solely from mineral liberation (Jafari et al., 2018; Liu et al., 2017; Ruan et al., 2018).

Roasting may improve flotation by increasing liberation, but it may also worsen flotation by producing heterogeneous oxidation states or residual carbonaceous surfaces. Studies on hematite depression, fungal cellulase depressants, eco-friendly apatite collectors, pullulan depressants, and low-temperature collectors for hematite–quartz separation show that reagent design increasingly targets surface-specific interactions rather than bulk mineral classes (Chen, Wang, et al., 2024; Ge et al., 2025; Guo et al., 2026; Peng et al., 2022; Wang et al., 2022; Yehia et al., 2021).

The effectiveness of apatite flotation depends on the selection and interaction of collectors, depressants, dispersants, and solution modifiers. These reagents control mineral surface properties, adsorption, pulp chemistry, and particle dispersion, impacting phosphate recovery and concentrate quality. As summarized in Table 6, each reagent class has a specific function in the flotation circuit, though mineralogical variability, changes in oxidation state, reagent consumption, and pulp chemistry constraints often impose operational limitations.

Table 6. Main flotation reagent systems relevant to apatite recovery and iron oxide depression after roasting-assisted beneficiation. Adapted from Derqaoui et al. (2022), Ruan et al. (2018, 2019), Wang et al. (2022), Ge et al. (2025), Yehia et al. (2021), and Guo et al. (2026).

Fatty acid collector	Sodium oleate	Apatite flotation	8–10	Iron oxide activation
Collector blends	Natural oils/fatty acids	Phosphate recovery	8–11	Froth instability
Depressant	Starch/cellulase/pullulan	Iron oxide depression	8–11	Oxidation-state sensitivity
Dispersant/depressant	Sodium silicate	Gangue dispersion	8–10	High dosage demand
Modifier	Sodium carbonate	pH and ionic control	8–11	Ionic strength increase

Table 6 demonstrates that flotation performance is governed not only by collector selection but also by depressants, dispersants, and pulp modifiers. Fatty-acid collectors are popular for apatite flotation due to their strong affinity for calcium minerals, but their selectivity drops if iron oxides activate or ions alter adsorption.

The table also highlights the importance of depressants and dispersants in controlling concentrate quality. Starch-based reagents, polysaccharides, and sodium silicate are commonly employed to suppress iron-bearing minerals and disperse gangue particles, thereby improving apatite selectivity. Nevertheless, their effectiveness may vary substantially with the mineral oxidation state, surface chemistry, particle-size distribution, and water composition. Consequently, reagent optimization should be considered a dynamic process that must be adjusted according to mineralogical characteristics and operating conditions rather than relying on fixed reagent schemes.

7.3. Hydrometallurgical Upgrading

Hydrometallurgical upgrading after roasting has gained interest as thermal activation can enhance acid access and phosphorus dissolution. Acid leaching often uses sulfuric, hydrochloric, or nitric acid based on mineralogy and downstream needs. Microwave-assisted liberation prior to acid leaching can improve phosphorus accessibility in high-phosphorus iron ores (Cai et al., 2018).

Alkaline leaching systems based on sodium hydroxide or sodium carbonate may selectively dissolve phosphorus-bearing phases or remove impurities from refractory concentrates. High-pressure alkaline leaching and ultrasonic acid leaching demonstrate that chemical upgrading can complement roasting when phosphorus is not sufficiently rejected by magnetic separation or flotation (Hu et al., 2025b).

Combined acid–alkaline systems and chemical separation strategies may improve phosphorus recovery and impurity control, but they increase reagent consumption, corrosion risk, effluent treatment requirements, and process complexity (Ali & Yassin, 2025; Pan et al., 2022; Sparrow et al., 2022).

Thermal processing modifies surface properties and flotation behavior of apatite-bearing iron ores by altering surface chemistry, defect density, roughness, and reagent adsorption. These changes affect how collectors and depressants interact, impacting flotation selectivity and concentrate quality. Figure 8 outlines how roasting and thermal treatment enhance flotation by changing mineral surface chemistry.

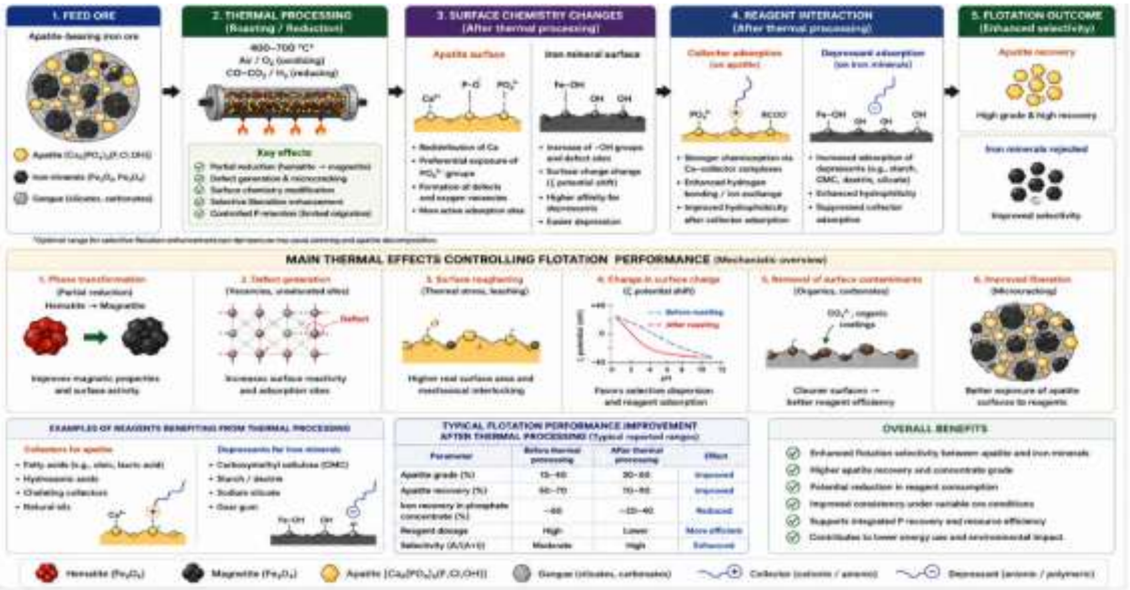


Figure 8. Effect of thermal processing on flotation selectivity and hydrometallurgical response of apatite-bearing systems. Adapted from Chen, Wang, et al. (2024), Yehia et al. (2021), Peng et al. (2022), Hu et al. (2025b), and Sparrow et al. (2022).

Figure 8 shows that thermal processing affects flotation via multiple physicochemical mechanisms, not just one. Controlled heat promotes the hematite-to-magnetite transformation, creates lattice defects and microcracking, and redistributes surface-active species, thereby altering reagent adsorption. These changes expose reactive apatite sites and increase depressant affinity for iron minerals.

The figure highlights how surface chemistry evolves during thermal treatment, affecting collector adsorption, hydrophobicity, and dispersion. Thermally treated apatite systems often exhibit improved flotation selectivity, higher phosphate recovery, and lower iron in concentrates.

Thermal pretreatment effectiveness depends on roasting temperature, atmosphere, residence time, mineralogy, and particle liberation. Excessive heat can cause sintering, apatite decomposition, or unwanted phase interactions, whereas controlled, mild heating can enhance reagent efficiency and flotation stability. Thermal processing acts as a surface-engineering approach to modify mineral–reagent interactions and improve phosphate recovery.

8. INTEGRATED HYBRID FLOWSHEETS AND INDUSTRIAL INTEGRATION

Integrated hybrid flowsheets have emerged as one of the most promising approaches for the beneficiation of magnetite–apatite ores because no single processing route consistently achieves simultaneous high iron recovery, effective phosphorus rejection, high-grade phosphate concentrates, and acceptable energy efficiency. The complexity of mineral associations, phosphorus distribution, and phase-transformation behavior requires beneficiation strategies that combine thermal, physical, surface-chemical, and hydrometallurgical operations within a coordinated process architecture.

Roasting is increasingly viewed as an enabling stage rather than a stand-alone beneficiation method. Thermal treatment modifies iron mineralogy, phosphorus partitioning, liberation behavior, particle friability, and surface chemistry, thereby influencing the effectiveness of all downstream separation processes. Consequently, the success of roasting-assisted beneficiation depends not only on roasting conditions themselves but also on how thermal activation is integrated with subsequent upgrading stages.

One of the most widely investigated configurations combines magnetization roasting with magnetic separation. In these systems, thermal treatment converts weakly magnetic iron phases into magnetite, thereby improving magnetic recovery. However, magnetic separation alone is rarely sufficient when phosphorus remains associated with composite particles or phosphate-bearing phases. For this reason, magnetic separation is frequently followed by flotation or chemical upgrading stages designed to selectively recover or reject phosphorus-bearing minerals (Pan et al., 2022; Xiao & Zhou, 2019).

Recent studies have expanded this concept toward more sophisticated hybrid flowsheets. These routes may combine selective reduction roasting, magnetic separation, flotation, additive-assisted dephosphorization, acid leaching, alkaline leaching, or smelting-based upgrading depending on ore mineralogy and processing objectives (Gong et al., 2025; Hu et al., 2025a, 2025c; Li et al., 2025; Qin et al., 2026; Wu et al., 2023, 2026). Such integrated systems aim to simultaneously maximize iron recovery, preserve phosphate value, and control phosphorus contamination throughout the beneficiation chain.

Dry beneficiation technologies also represent an important area of development. Dry magnetic separation, triboelectrostatic concentration, and hybrid dry-processing concepts may reduce water consumption and simplify tailings management in arid regions. Although these technologies still face challenges associated with fine-particle control and separation selectivity, they offer potential advantages when integrated with selective thermal activation and reduced water usage (Guo et al., 2024).

The growing emphasis on integrated beneficiation reflects a broader shift in process design philosophy. Rather than maximizing a single performance indicator such as metallization or iron recovery, future flowsheets are increasingly designed to optimize multiple objectives simultaneously, including phosphorus management, phosphate upgrading, energy efficiency, environmental performance, and operational flexibility

Recent studies show no single beneficiation process can achieve high iron recovery, phosphorus rejection, high-grade phosphate concentrates, and low-energy processing for magnetite–apatite ores under all conditions. Therefore, hybrid flowsheets combining roasting, magnetic separation, flotation, and hydrometallurgy are gaining interest. These methods aim to improve phase control, reduce phosphorus migration, secondary phases, and reagent use. Figure 9 illustrates an integrated flowsheet for phosphate recovery using thermal activation, physical separation, flotation, and hydrometallurgy.

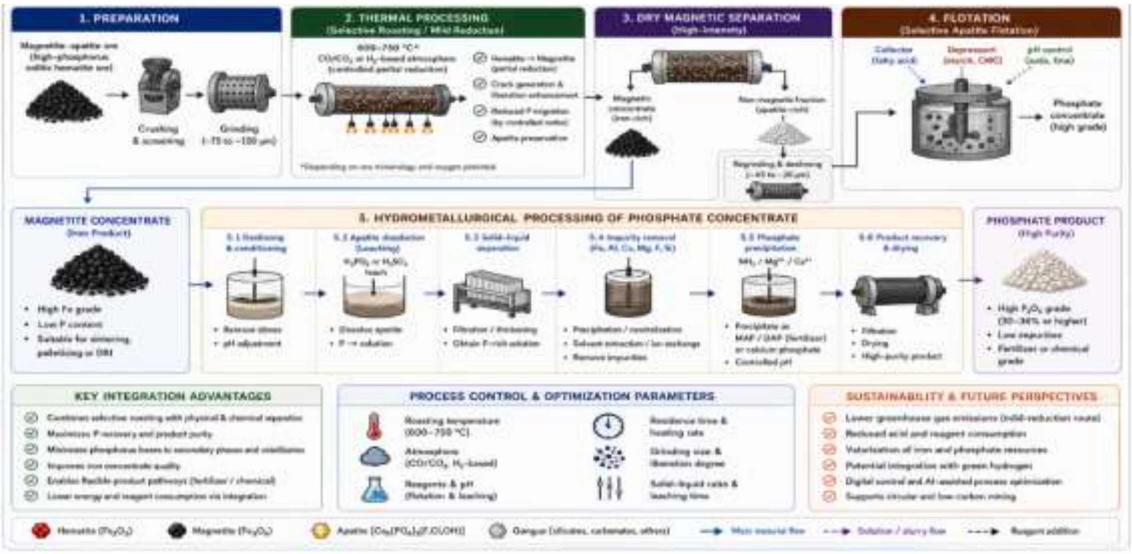


Figure 9. Proposed hybrid flowsheets integrating selective roasting, magnetic separation, flotation, and hydrometallurgical processing for high-grade phosphate recovery from magnetite–apatite ores. The framework emphasizes controlled phase transformation, selective liberation, phosphorus upgrading, and integrated low-energy beneficiation. Adapted from Pan et al. (2022), Wu et al. (2023), and Qin et al. (2026).

Figure 9 illustrates how future beneficiation systems may evolve from isolated unit operations toward integrated processing architectures capable of simultaneously addressing iron recovery, phosphorus control, and phosphate upgrading. In these systems, roasting primarily serves as a selective activation stage that modifies mineralogy, liberation characteristics, and surface properties prior to downstream separation.

The proposed framework highlights the importance of controlling phosphorus partitioning throughout the beneficiation chain. By combining selective thermal activation with magnetic separation, flotation, and hydrometallurgical purification, it becomes possible to improve resource utilization while reducing phosphorus contamination and minimizing losses of valuable phosphate-bearing phases.

The emerging trend is therefore not toward increasingly aggressive reduction conditions, but toward integrated beneficiation systems that combine thermal activation, physical separation, surface-chemical control, and chemical upgrading in a coordinated and resource-efficient manner.

9. INDUSTRIAL SCALE-UP AND SUSTAINABILITY

Although roasting-assisted beneficiation has demonstrated considerable technical potential at laboratory scale, industrial implementation remains relatively limited. The transition from laboratory investigations to commercial operation introduces numerous scale-dependent challenges that are rarely captured under controlled experimental conditions. Consequently, successful industrial deployment depends not only on beneficiation performance but also on process stability, energy consumption, environmental impact, and economic viability.

One of the principal scale-up challenges is thermal heterogeneity. Laboratory studies typically employ small samples with relatively uniform heating conditions, whereas industrial roasting systems must process large volumes of material under complex heat-transfer environments. Variations in temperature distribution, gas flow, particle segregation, and residence-time distribution may significantly affect phase transformations, reduction behavior, phosphorus migration, and final concentrate quality. As a result, roasting conditions that appear optimal at laboratory scale may not necessarily translate directly to industrial performance.

Atmosphere control represents another critical issue. Selective beneficiation relies heavily on controlling oxygen potential and reduction intensity. However, maintaining homogeneous gas composition throughout large-scale rotary kilns, fluidized beds, suspension roasters, or shaft furnaces is substantially more difficult than under laboratory conditions. Local variations in reducing potential may lead to inconsistent phase transformations, heterogeneous phosphorus partitioning, and variable beneficiation performance.

Pilot-scale investigations provide valuable insight into these challenges. Rotary-kiln studies have demonstrated that reduced iron concentrates can be produced from phosphorus-bearing ores, but process stability depends strongly on thermal uniformity, residence-time control, and atmosphere management (You et al., 2024). Similarly, flotation systems operating at pilot or industrial scale often experience broader particle-size distributions, more complex water chemistry, variable mineral exposure, and fluctuating reagent adsorption behavior compared with bench-scale tests. These factors may substantially influence phosphate recovery and concentrate quality (Angelopoulos et al., 2025).

A major limitation of the current knowledge base is the imbalance between mechanistic understanding and industrial validation. Most published studies focus on thermodynamic behavior, phase transformations, liberation mechanisms, magnetic separation performance, or flotation response under controlled laboratory conditions. In contrast, comparatively few investigations report pilot-scale campaigns, continuous operation, process economics, long-term equipment performance, operational reliability, or industrial-scale environmental assessments. This disparity remains one of the principal obstacles to commercial implementation.

The evidence base further reflects a strong concentration of laboratory-scale studies relative to pilot-scale and industrial investigations. Consequently, many emerging concepts—including selective mild reduction, additive-assisted roasting, phosphorus-directed phase control, and integrated phosphate recovery—remain scientifically promising but insufficiently validated under realistic industrial conditions. Future research should therefore prioritize pilot-scale demonstrations, industrial campaigns, and techno-economic assessments capable of bridging the gap between laboratory observations and commercial deployment.

Sustainability considerations are becoming increasingly important in process selection and technology development. Roasting operations consume significant amounts of thermal energy and may generate carbon dioxide, particulate emissions, nitrogen oxides, sulfur-containing gases, and dust depending on process configuration and ore composition. Therefore, improvements in beneficiation performance must be evaluated alongside energy demand, emission intensity, and gas-treatment requirements.

Water management constitutes an additional sustainability challenge. Conventional flotation and hydrometallurgical circuits may require substantial freshwater consumption, whereas hybrid flowsheets incorporating dry beneficiation and selective roasting may reduce water demand. However, these approaches typically require enhanced dust-control systems and stricter particle-size management. Consequently, future process development should seek to optimize recovery, concentrate quality, water consumption, energy efficiency, and environmental performance simultaneously.

The long-term sustainability of roasting-assisted beneficiation will likely depend on the adoption of lower-temperature activation strategies, renewable reductants, hydrogen-rich atmospheres, waste-derived additives, heat-recovery systems, and advanced process-control technologies. Digital twins, machine learning tools, and real-time monitoring systems may further improve process efficiency by enabling predictive control of phase transformations, phosphorus partitioning, and energy consumption.

Table 7 summarizes the maturity of roasting-assisted beneficiation routes by process complexity, thermal control, and scalability. Laboratory work primarily explores phase transformations and mechanisms, while pilot- and demonstration-scale studies evaluate process integration, thermal stability, atmospheric control, and beneficiation performance under realistic conditions.

Table 7. Industrial and pilot-scale limitations associated with roasting-assisted beneficiation. Adapted from You et al. (2024), Angelopoulos et al. (2025), Zhang et al. (2022), Ofoegbu (2019), and Faris et al. (2017)

Laboratory	Selective reduction	Mechanistic control	Limited scale validation	3–4
Pilot	Magnetization roasting	Improved Fe recovery	Thermal heterogeneity	5–6
Pilot	Rotary-kiln reduction	Process realism	Atmosphere/residence-time control	5–6
Pilot	Flotation after roasting	Selectivity assessment	Pulp chemistry variability	4–6
Industrial demonstration	Oxidizing/magnetizing roasting	Higher concentrate grade	Energy and emission burden	6–7

Table 7 demonstrates that technological maturity varies substantially among roasting-assisted beneficiation routes. Laboratory-scale investigations provide critical mechanistic understanding of phase transformations, phosphorus migration, and liberation behavior, whereas pilot-scale studies offer more realistic assessments of thermal stability, atmosphere control, and process integration. However, relatively few technologies have progressed beyond pilot demonstration toward sustained industrial operation.

The table further highlights that the principal barriers to industrial implementation are no longer limited to beneficiation performance itself. Instead, challenges increasingly involve thermal management, atmosphere control, emissions, energy demand, operational stability, and overall process economics. Future technological development must therefore address both beneficiation efficiency and industrial practicality if roasting-assisted beneficiation is to achieve widespread commercial adoption.

10. RESEARCH GAPS AND FUTURE DIRECTIONS

Despite significant progress in roasting-assisted beneficiation of magnetite–apatite ores, several scientific and technological gaps remain unresolved. Much of the available literature continues to emphasize iron recovery, magnetic separation efficiency, or phosphorus removal performance as isolated metrics, whereas considerably less attention has been devoted to the coupled relationships among mineralogical texture, thermodynamic stability, reduction kinetics, phosphorus partitioning, liberation behavior, flotation selectivity, and downstream process integration. As a result, beneficiation performance is often reported without a comprehensive understanding of the mechanisms controlling phosphorus redistribution and concentrate quality.

Methodological limitations further complicate interpretation of the current knowledge base. Many studies do not report critical processing variables such as oxygen potential, gas composition, residence-time distribution, heating and cooling rates, phosphorus mass balances, or phase-specific phosphorus distribution. The lack of standardized reporting practices hinders comparison among studies and reduces the reproducibility of experimental results. In addition, the literature remains dominated by laboratory-scale investigations, whereas pilot-scale demonstrations, industrial validation campaigns, and long-term operational studies are comparatively scarce. This imbalance limits confidence in the scalability of many proposed beneficiation routes and represents one of the most significant barriers to industrial implementation.

The evidence base itself exhibits a marked disparity in technological maturity. Laboratory studies have substantially improved the mechanistic understanding of phase transformations, magnetic enhancement, phosphorus migration, and flotation behavior. However, relatively few studies evaluate continuous operation, process control, energy consumption, emissions, equipment performance, operational reliability, or techno-economic feasibility under industrial conditions. Consequently, the practical applicability of selective mild reduction, additive-assisted roasting, and integrated phosphate recovery concepts remains insufficiently validated despite their promising laboratory-scale results.

Future research should therefore prioritize pilot-scale campaigns, industrial demonstration studies, and structured techno-economic assessments capable of bridging the gap between mechanistic understanding and commercial deployment. Greater emphasis should also be placed on evidence quality assessment and on the explicit differentiation among laboratory, pilot, industrial, modeling, and review studies to improve the reliability of future syntheses and technology evaluations.

From a scientific perspective, several priority research directions can be identified. Selective moderate-temperature reduction requires further investigation to establish robust operating windows that maximize magnetic enhancement while minimizing phosphorus transfer into metallic iron. Predictive models linking oxygen potential, temperature, mineral texture, degree of reduction, and phosphorus partitioning remain underdeveloped and should be a major focus of future work. Similarly, coupled thermo-mechanical simulations that capture crack initiation, interfacial weakening, selective liberation, and grinding behavior would substantially improve process optimization and the reliability of scale-up.

Advanced characterization techniques, like synchrotron-based methods, high-temperature microscopy, X-ray diffraction, and spectroscopy, enable in situ monitoring of phase transformations. This could reveal phosphorus redistribution and phase evolution during roasting, clarifying issues around apatite stability, secondary phosphate formation, and the magnetite-to-iron transition.

A conceptual hierarchy of controlling variables guides future research: mineral texture affects liberation; oxygen potential influences iron phases; degree of reduction controls phosphorus mobility; thermal stress induces cracks; surface chemistry affects flotation; process integration determines industrial feasibility. Understanding how these variables interact is key to developing predictive beneficiation models beyond empirical methods.

Future roasting-assisted beneficiation will favor selective thermal activation over maximum metallization. Excessive reducing conditions can increase phosphorus migration, destabilize apatite, promote the formation of secondary phases, and reduce flotation selectivity. Mild-reduction methods can improve liberation, preserve phosphate phases, reduce impurities, cut energy use, and boost resource efficiency. Figure 10 outlines this new approach and a framework for next-gen systems.

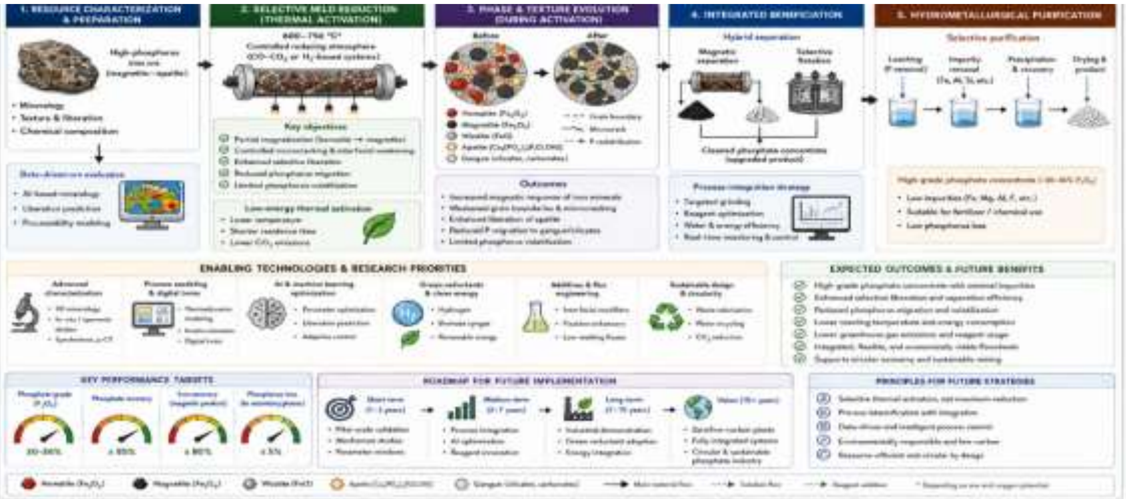


Figure 10. Proposed future framework for selective moderate-temperature roasting of magnetite–apatite ores emphasizing controlled phosphorus partition, selective liberation, surface-chemistry preservation, and energy-efficient beneficiation. Adapted from Wu et al. (2023), Xu et al. (2025), Pan et al. (2022), Pereira and Papini (2015), and Li et al. (2025).

Figure 10 shows the shift from high-intensity reduction roasting to selective, process-oriented thermal activation. Instead of maximizing metallization, it focuses on controlled phase transformation, apatite preservation, phosphorus management, and microstructural engineering to enhance separation. Incorporating selective roasting with magnetic separation, flotation, hydrometallurgy, digital control, and modeling can lead to more sustainable, cost-effective beneficiation.

The framework emphasizes the growing role of thermodynamic modeling, machine learning, AI, digital twins, and adaptive process optimization. These tools can enhance prediction of beneficiation response, support real-time control, and reduce scale-up uncertainty. Success depends on high-quality pilot and industrial datasets, which are currently limited. Expanding these datasets should be a strategic priority for advancing roasting-assisted beneficiation technologies.

11. CONCLUSIONS

Roasting-assisted beneficiation is an important strategy for processing magnetite–apatite ores because thermal treatment modifies the stability of iron phases, liberation behavior, magnetic susceptibility, and phosphorus partitioning. However, the review demonstrates that beneficiation selectivity depends more strongly on controlled thermal activation than on maximum metallization.

Moderate-temperature roasting between approximately 650 and 800 °C generally provides a more favorable balance between iron recovery and phosphorus control than aggressive high-temperature reduction. Strongly reducing conditions may increase metallic iron formation but also promote phosphorus transfer toward metallic iron, Fe–P phases, slag, or secondary phosphates.

Mineral texture remains the first-order constraint. Fine apatite encapsulation, grain-boundary locking, secondary phosphate formation, and hydrothermal alteration may limit the benefits of roasting even when magnetic response improves.

Roasting also affects flotation and hydrometallurgical upgrading through surface oxidation, reagent adsorption changes, crack propagation, acid accessibility, and impurity dissolution. Therefore, roasting should be designed as part of an integrated flowsheet rather than as an isolated unit operation.

Industrial implementation remains constrained by thermal heterogeneity, atmosphere control, energy demand, dust and gas treatment, reagent management, and limited pilot-scale validation. Future development should prioritize selective low-temperature activation, oxygen-potential control, quantitative phosphorus mass balance, coupled thermodynamic–microstructural modeling, and integrated beneficiation flowsheets capable of improving iron recovery and phosphate upgrading while reducing energy and environmental burden.

Overall, roasting-assisted beneficiation is evolving from aggressive metallization-oriented processing toward selective moderate-temperature activation focused on controlled phosphorus partition, improved liberation, surface-chemistry preservation, and integrated resource utilization.

Declarations

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Conflicts of Interest

The author declares no conflict of interest.

Data Availability Statement

The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

Author Contributions

Conceptualization, methodology, investigation, formal analysis, writing—original draft preparation, writing—review and editing: A.C.P.

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