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Toward Sustainable Utilization of Low-Grade Ilmenite: An Integrative Review of Beneficiation Technologies, Resource Recovery, and Circular Economy Strategies

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ABSTRACT

Declining rutile availability and increasingly complex ilmenite resources require processing strategies that extend beyond titanium recovery alone. This review examines how low-grade ilmenite can support economically viable and environmentally responsible production of titanium and associated critical minerals. The review followed PRISMA 2020 guidelines and assessed literature published between January 2016 and June 2026 across six scientific databases. Evidence was synthesised on mineralogical controls, beneficiation, metallurgical upgrading, co-product recovery, waste valorisation, life-cycle performance, techno-economics, and digital process integration. The findings show that TiO_2 grade alone cannot predict beneficiation performance. Liberation, alteration state, gangue association, and surface chemistry determine the suitability of each flowsheet. Gravity, magnetic, electrostatic, and flotation methods perform best within specific particle-size and mineralogical ranges. Hybrid circuits provide more consistent recovery from fine and altered ores. Standalone titanium recovery often remains economically marginal, whereas co-recovery of iron, vanadium, scandium, rare earth elements, and zirconium can improve project viability. Hydrogen-based reduction offers substantial decarbonisation potential, although limited technology readiness and green hydrogen costs constrain near-term deployment. Closed-loop acid regeneration, water reuse, and residue valorisation reduce environmental burdens, but inconsistent life-cycle boundaries and allocation methods prevent reliable comparison across studies. Sustainable utilisation will require mineralogy-driven flowsheet design, harmonised assessment protocols, pilot-scale validation, and integrated recovery systems supported by real-time sensing and digital process control.

1. INTRODUCTION

Titanium combines low density, high specific strength, and corrosion resistance, making it suitable for aerospace structures, chemical processing equipment, marine systems, and biomedical devices. Titanium dioxide (TiO_2) is also the dominant white pigment, while applications in energy storage, photocatalysis, and functional nanomaterials are increasing demand (Munonde & Raphulu, 2024). Primary production depends mainly on ilmenite ($FeTiO_3$) and rutile (TiO_2). Depletion of natural rutile is shifting industry toward lower-grade ilmenite deposits with fine intergrowths, complex gangue, and elevated impurities (Torres-Mejia *et al.,* 2026; Wang *et al.,* 2024). Average ore grades have declined and are expected to fall further as high-quality reserves are depleted (Perks & Mudd, 2021; Sverdrup & Sverdrup, 2023). Feedstock quality and processing

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compatibility, rather than total resource availability, now constrain titanium production.

Bulk TiO_2 grade alone does not determine the value of an ilmenite resource. Processing performance depends on mineralogy, alteration state, crystal chemistry, liberation size, and gangue association. In the Panzhihua titanomagnetite tailings, for example, titanium-bearing phases are tightly intergrown with hematite and silicate minerals (Zhai *et al.,* 2017). Such intergrowths limit gravity, magnetic, and electrostatic separation, particularly at ultrafine particle sizes. Flotation can recover finer particles but often lacks selectivity against reactive silicate and pyroxene gangue (Zhai *et al.,* 2020; Nzeh & Popoola, 2024). Weathering adds further variability by converting ilmenite into pseudorutile and leucoxene, thereby changing magnetic susceptibility, surface charge, and electrical conductivity within the same orebody. Conventional physical circuits consequently produce sub-specification concentrates and lose considerable titanium to tailings (Zhai *et al.,* 2020; Wang *et al.,* 2024).

Complex ores therefore require physical beneficiation to be integrated with pyrometallurgical or hydrometallurgical upgrading to produce marketable titanium slag or synthetic rutile. These additional stages impose environmental and economic costs. Fine grinding raises specific energy consumption, while chemical upgrading produces large volumes of waste. The sulfate pigment process alone generates about one million tonnes of acidic ilmenite mud annually (Chyliński *et al.,* 2020; TahooniBonab *et al.,* 2025). Life-cycle assessments identify sulfuric acid, electricity, and thermal energy as major sources of toxicity and greenhouse gas emissions across titanium production (Dai *et al.,* 2024).

Low-grade ilmenite may also contain economically relevant iron, vanadium, scandium, rare earth elements, chromium, and zirconium (Morin-Ka *et al.,* 2025). Recovering these elements can improve project economics and reduce dependence on titanium revenue. Tailings and slags may also serve as feedstocks for construction materials, lowering disposal requirements and associated environmental liabilities (Feng *et al.,* 2023; Hu *et al.,* 2024; Torres-Mejia *et al.,* 2026; Cotrina-Teatino & Marquina-Araujo, 2025). These opportunities cannot be assessed through titanium recovery alone. Process performance, co-product value, energy and water use, emissions, and residual waste must be evaluated within the same framework.

Previous reviews have been summarized in Table 1. These reviews examined separate parts of the titanium value chain. Their main subjects include flotation chemistry (Zhai *et al.,* 2020), resource and production trends (Perks & Mudd, 2021), physical beneficiation (Wang *et al.,* 2024), recovery from vanadium‑titanium magnetite tailings (Hu *et al.,* 2024), hydrometallurgical extraction (TahooniBonab *et al.,* 2025), and circular economy practices across mining (Cotrina-Teatino & Marquina-Araujo, 2025). None integrates mineralogical controls, beneficiation, metallurgical upgrading, critical-mineral recovery, waste valorisation, sustainability assessment, and digitalisation across the complete low-grade ilmenite value chain. Machine learning and intelligent sensor sorting also remain underexamined in ilmenite processing, despite their potential to support feed-responsive process control (Szmigiel *et al.,* 2024). A second gap lies between laboratory performance and commercial application. Promising technologies often remain undeployed because of scale-up uncertainty, variable feed mineralogy, inconsistent life-cycle boundaries, volatile co-product markets,

and regulatory restrictions on the reuse of mineral-processing residues.

This review addresses both gaps by linking mineralogical characteristics to process selection and evaluating beneficiation routes within broader metallurgical, environmental, economic, and circularity contexts. It also identifies the conditions under which integrated recovery and digital process control could make low-grade ilmenite a viable source of titanium and associated critical minerals.

Table 1: Comparison of recent reviews on ilmenite processing and titanium-resource utilisation

Review	**Primary focus**	**Beneficiation**	**Metallurgical upgrading**	**Secondary-resource recovery**	**Critical-mineral recovery**	**Sustainability assessment**	**Circular economy**	**Digital technologies**	**Principal scope limitation**
Zhai *et al.* (2020)	Ilmenite flotation chemistry	✓	—	—	—	—	—	—	Restricted to flotation reagents and surface chemistry; excludes downstream processing and sustainability
Perks and Mudd (2021)	Titanium-resource and production trends	Limited	—	—	Limited	—	—	—	Describes resource availability without evaluating processing or utilisation strategies
Wang *et al.* (2024)	Ilmenite beneficiation technologies	✓	Limited	—	—	Limited	—	—	Emphasises physical beneficiation, with limited treatment of downstream upgrading and circularity
Hu *et al.* (2024)	Recovery from vanadium–titanium magnetite tailings	Limited	✓	✓	Partial	Partial	Partial	—	Addresses vanadium–titanium magnetite waste rather than ilmenite resources
Tahooni-Bonab *et al.* (2025)	Hydrometallurgical extraction	—	✓	Limited	—	Limited	—	—	Reviews leaching without integrating upstream beneficiation or resource management
Cotrina-Teatino and Marquina-Araujo (2025)	Circular economy in mining	—	—	✓	Limited	✓	✓	—	Provides a sector-wide assessment without titanium-specific analysis
This review	Sustainable utilisation of low-grade ilmenite	✓	✓	✓	✓	✓	✓	✓	Integrates ore characterisation, beneficiation, upgrading, resource recovery,

									sustainability, circularity, and digitalisation

1.1 Review Methodology

The review followed the PRISMA 2020 guidelines to provide a transparent and reproducible evidence-selection process (Page *et al.,* 2021). Scopus, Web of Science, ScienceDirect, SpringerLink, IEEE Xplore, and Google Scholar were searched for studies published between January 2016 and June 2026. The search string combined terms relating to ilmenite resources, processing technologies, resource recovery, and sustainability outcomes. Earlier studies were retained when they provided foundational mineralogical or process evidence. Table 2 presents the eligibility criteria.

Table 2. Study eligibility criteria

Criterion	**Inclusion**	**Exclusion**
Publication type	Peer-reviewed journal articles and conference papers	Patents, unpublished theses, and non-peer-reviewed reports
Language	English	Non-English publications without certified translations
Subject focus	Low-grade or complex ilmenite ores and sustainable or circular recovery strategies	High-grade ilmenite processing without waste-valorisation or circularity relevance
Publication period	2016–2026	Pre-2016 studies, except seminal or foundational works
Content scope	Beneficiation, resource recovery, and tailings or red-mud valorisation	Geological or exploratory studies without a processing dimension
Data availability	Studies reporting quantitative process or performance data	Abstract-only publications and studies with insufficient data

2. GEOLOGICAL OCCURRENCE AND MINERALOGICAL CHARACTERISTICS OF LOW-GRADE ILMENITE

Declining natural rutile resources and growing demand from the pigment, aerospace, energy, and defence sectors have increased reliance on ilmenite as the principal titanium feedstock (USGS, 2024; USGS, 2025; Wang *et al.,* 2024). This shift has brought low-grade, fine-grained, and mineralogically complex deposits into consideration, including resources previously regarded as uneconomic (USGS, 2025). Titanium's designation as a critical mineral in several major economies further supports diversification into lower-grade ores and secondary resources (USGS, 2025).

The economic value of these resources cannot be inferred from bulk TiO_2 grade alone. Geological history determines grain morphology, crystal chemistry, alteration, texture, and gangue association. These characteristics control liberation and the response of an ore to grinding, magnetic separation, flotation, and hydrometallurgical treatment. Deposits with similar TiO_2 grades may therefore require different flowsheets and produce markedly different recoveries (Wang *et al.,* 2024). Mineralogical variability is both the main processing constraint and the basis for selecting an effective beneficiation route.

2.1 Global Distribution of Deposit Types

Ilmenite occurs mainly in primary magmatic deposits, beach placers, and

secondary resources such as laterites, weathered crusts, and tailings. Each deposit type reflects a distinct formation history and beneficiation response. Magmatic ilmenite commonly occurs as angular grains intergrown with titanomagnetite and silicate minerals. Extensive locking requires fine comminution, but improved liberation comes at the cost of higher energy consumption, overgrinding, and slime generation (Robinson *et al.,* 2004; McEnroe *et al.,* 2007; Wang *et al.,* 2024).

Beach placers are generally more amenable to physical beneficiation. Prolonged weathering, transport, and hydraulic sorting produce rounded and naturally liberated heavy-mineral grains. Gravity and magnetic separation can therefore recover relatively high-grade concentrates with less comminution than hard-rock ores require (Ramakokovhu *et al.,* 2020; Nzeh & Popoola, 2023). Secondary resources present a different challenge. Laterites, weathered crusts, and tailings are typically heterogeneous, fine-grained, and coated with clays or secondary iron phases. These features weaken the performance of conventional physical separation and often require combined physical and surface-chemical treatment (Nzeh & Popoola, 2024; USGS, 2025). Geological origin consequently determines not only ore composition but also the range of technically feasible beneficiation routes.

2.2 Mineralogical Fingerprinting

Natural ilmenite rarely conforms to the ideal $FeTiO_3$ composition. Substitution by Mg^{2+}, Mn^{2+}, and minor V produces compositional shifts toward geikielite and pyrophanite. These substitutions alter density, magnetic susceptibility, electrical conductivity, surface charge, and collector adsorption (Mehdilo *et al.,* 2015; Wang *et al.,* 2024). A separation regime developed for one deposit may therefore perform poorly on another, even when their bulk TiO_2 grades are similar.

Exsolution within the hematite–ilmenite solid-solution series introduces additional constraints. Slow magmatic cooling produces micron- to nanoscale hematite lamellae that modify magnetic behaviour and fracture response. During comminution, particles may fracture across these lamellae rather than along mineral boundaries, leaving composite grains that limit concentrate grade (Robinson *et al.,* 2004; McEnroe *et al.,* 2007). This explains why optimised magnetic separation may still fail to meet market specifications and why complex ores often require pyrometallurgical or hydrometallurgical upgrading (Wang *et al.,* 2024).

Gangue minerals influence both separation efficiency and resource value. Quartz and feldspar reduce the density contrast required for gravity separation. Titanomagnetite, chromite, and other iron oxides may overlap with ilmenite in magnetic susceptibility, reducing magnetic selectivity. Zircon, rutile, and monazite complicate circuit design but can provide additional revenue when the flowsheet supports their recovery (Nzeh & Popoola, 2023, 2024). Surface oxidation also changes the Fe^{2+}/Fe^{3+} ratio and isoelectric point, affecting collector adsorption and flotation selectivity (Semsari Parapari *et al.,* 2016; Chen *et al.,* 2023). Mineralogical fingerprinting must therefore extend beyond phase identification to quantify composition, surface condition, grain associations, and liberation. However, the relationships between trace-element substitution, surface chemistry, and plant-scale performance remain insufficiently defined across deposit types.

2.3 Factors Constraining Beneficiation

Weathering may improve chemical grade while weakening beneficiation response. Progressive iron leaching converts ilmenite through leached ilmenite and pseudorutile into leucoxene. This process raises TiO_2 content but produces porous, compositionally variable grains with inconsistent magnetic properties (Grey & Reid, 1975; Mücke & Bhadra Chaudhuri, 1991). Evidence from Egyptian black

sands shows that successive alteration stages respond differently to magnetic separation. Fixed separator conditions are therefore unlikely to perform consistently across heterogeneous ore bodies (Moustafa, 2023a, 2023b).

Alteration also changes the mineral surface. Oxide films, clay coatings, and secondary iron phases can mask active sites and reduce flotation selectivity. Desliming and surface conditioning may restore selectivity, but they can also remove titanium-bearing ultrafines and lower overall recovery (Ramakokovhu *et al.,* 2020; Nzeh & Popoola, 2024). The literature does not support a single interpretation of alteration as either beneficial or detrimental. Moderate weathering may weaken grain boundaries and improve liberation, whereas advanced alteration can generate slimes and unstable surface properties. The net effect depends on alteration intensity, mineral assemblage, and the balance between improved breakage and impaired separation.

2.4 Liberation Behaviour

Liberation establishes the practical limit of beneficiation because separation requires exposed mineral grains rather than particle-size reduction alone (Semsari Parapari *et al.,* 2020; Guntoro *et al.,* 2019). Fine intergrowths between hard-rock ilmenite, titanomagnetite, and silicate gangue demand intensive grinding. Further size reduction may improve exposure but also increases energy use, overgrinding, and titanium losses to slimes (Robinson *et al.,* 2004; Wang *et al.,* 2024).

Placer deposits avoid much of this penalty because sedimentary transport provides natural liberation. Weathered ores occupy an intermediate position. Microfracturing can reduce comminution requirements, but the resulting grains are often fragile and prone to generating ultrafines during processing (Mücke & Bhadra Chaudhuri, 1991; Ramakokovhu *et al.,* 2020; Nzeh & Popoola, 2023). Automated mineralogical analysis confirms that concentrate grade and recovery remain bounded by the degree of liberation (Sousa *et al.,* 2018). Circuit design must therefore balance finer grinding for mineral exposure against coarser grinding that limits energy consumption and slime losses. Predictive models linking ore texture, alteration, and breakage behaviour are still needed to identify this optimum for individual deposits.

2.5 Integrated Mineralogical Synthesis

Deposit-specific mineralogy, rather than TiO_2 grade alone, controls beneficiation performance. Geological origin determines crystal chemistry, alteration, grain size, texture, and gangue association. These properties govern liberation and the response of an ore to each downstream process (Robinson *et al.,* 2004; Mehdilo *et al.,* 2015; Wang *et al.,* 2024). Weathering illustrates this interaction clearly. Iron removal enriches TiO_2 but may also produce pseudorutile, leucoxene, clay coatings, variable magnetic behaviour, and loss-prone ultrafines (Mücke & Bhadra Chaudhuri, 1991; Moustafa, 2023a, 2023b).

Table 3 links the principal mineralogical characteristics of low-grade ilmenite to their beneficiation implications and appropriate processing responses. The comparison shows why no single technology is suitable for all deposits. Naturally liberated placer grains favour gravity-based concentration, whereas fine magmatic intergrowths require controlled comminution and staged magnetic separation. Weathered or surface-contaminated ores may need flotation, surface conditioning, or hydrometallurgical upgrading. Sustainable utilisation therefore depends on mineralogical characterisation conducted before flowsheet selection and optimisation.

Table 3. Mineralogical controls on beneficiation-route selection for low-grade ilmenite

Miner-alogical	**Beneficia-tion impli-cation**	**Preferred processing response**

character-istic		
Fine inter-growths with titan-omagnetite and silicate gangue	Poor liber-ation and restricted concen-trate grade	Controlled comminu-tion, staged magnetic separation, and down-stream up-grading
Rounded, naturally liberated placer grains	High re-covery at coarse par-ticle sizes and low comminu-tion de-mand	Gravity concentra-tion fol-lowed by magnetic and electro-static clean-ing
Alteration to pseu-dorutile and leu-coxene	Higher TiO_2 grade but varia-ble mag-netic and surface properties	Adaptive magnetic separation combined with flota-tion or hy-drometal-lurgical up-grading
Clay coat-ings, sec-ondary iron ox-ides, and slimes	Lower flo-tation se-lectivity and greater reagent de-mand	Desliming, surface condition-ing, and se-lective flo-tation
Trace-ele-ment sub-stitution and varia-ble Fe^{2+}/Fe^{3+} ratios	Changes in magnetic suscepti-bility, con-ductivity, and collec-tor adsorp-tion	Deposit-specific op-timisation of magnetic field strength, electrostatic conditions, and reagent schemes
Variable grain size, texture, and libera-tion	Trade-off among re-covery, concen-trate grade, energy use, and slime gen-eration	Liberation-based cir-cuit design supported by auto-mated min-eralogical characteri-sation

3. BENEFICIATION TECHNOLOGIES FOR LOW-GRADE ILMENITE

Beneficiation performance depends on ore mineralogy rather than the nominal capability of a separator. Coarse, liberated hard-rock ilmenite responds differently from weathered placer material dominated by pseudorutile and leucoxene because alteration changes density, magnetic susceptibility, conductivity, and surface chemistry (Pownceby *et al.,* 2008; Wang *et al.,* 2024). Egyptian black-sand ilmenite illustrates this relationship: pseudorutile and leached pseudorutile contained approximately 57–78% TiO_2, yet magnetic susceptibility declined as iron was removed during alteration (Moustafa, 2023). A deposit on the southern Brazilian coast showed a similar dependence of beneficiation potential on in situ alteration (Wust *et al.,* 2024). Particle size imposes another limit. Circuits designed for coarse, liberated grains lose substantial value in the sub-45 μm fraction, which represents a growing proportion of low-grade ilmenite resources (Motovilov *et al.,* 2026). Technology selection must therefore begin with alteration state, liberation size, and gangue characteristics rather than a flowsheet developed for another deposit (Wang *et al.,* 2024).

3.1 Conventional Beneficiation Technologies

Gravity concentration remains suitable for coarse, naturally liberated placer ilmenite because it is inexpensive, robust, and reagent-free (Wang *et al.,* 2024). Its

efficiency declines sharply below approximately 30–50 μm, which limits its application to fine-grained and altered ores (Motovilov *et al.,* 2026). At the Humma lean-grade beach placer, spiral concentration required subsequent magnetic and electrostatic separation, followed by microwave cleaning of the magnetic product (Raghupatruni & Satya, 2024). This arrangement reflects the present role of gravity concentration: a roughing stage that removes bulk silicate gangue before more selective operations (Liu *et al.,* 2024).

High-gradient magnetic separation (HGMS) extends recovery into finer size fractions and has largely replaced gravity concentration as the main roughing operation for weakly liberated ilmenite (Hu *et al.,* 2023). Its performance nevertheless varies widely with feed mineralogy. A gravity–magnetic circuit upgraded a feed containing 3.97% TiO_2 to 16.50% at 54.11% recovery (Liu *et al.,* 2025). Pulsating HGMS raised an ultrafine tailings feed from 4.33% to 13.64% TiO_2 at 66.55% recovery (Ahmed *et al.,* 2024), while superconducting HGMS produced 16.03% TiO_2 from a −20 μm feed at 66.39% recovery (Yuan *et al.,* 2021). Full-scale centrifugal HGMS achieved a stronger result, increasing grade from 15.25% to 32.49% TiO_2 at 81.07% recovery (Zhang *et al.,* 2024).

These results show that modified field configurations can improve recovery but do not remove the mineralogical limit on concentrate grade. Weakly magnetic gangue responds to the same field intensities required to capture fine ilmenite, causing concentrate grades to plateau below 50% where such gangue is abundant (Chu *et al.,* 2022; Liu *et al.,* 2025; Wang *et al.,* 2024). Reflux classification addresses part of this problem by limiting the entrainment of augite and chlorite. A laboratory reflux classifier achieved 50.0% separation efficiency, while an agitated reflux classifier produced comparable grade and recovery to the gravity–magnetic circuit reported above (Liu *et al.,* 2024). Separator configuration matters, but gangue susceptibility ultimately determines whether magnetic separation can produce a saleable concentrate (Hu *et al.,* 2023; Wang *et al.,* 2024).

Electrostatic separation uses conductivity differences between ilmenite and rutile, which are conductive, and zircon and silicate gangue, which are comparatively non-conductive. Industrial units commonly operate at approximately 21–26 kV and remain established in dry mineral-sands processing (Elder & Yan, 2003). The method requires dry, coarse, and well-liberated feed, making it unsuitable for moist, fine, or strongly altered material. At the Humma deposit, electrostatic cleaning became effective only after spiral and magnetic pre-concentration (Raghupatruni & Satya, 2024). Flotation has consequently displaced electrostatic separation where weathering and fine grain size prevent adequate physical separation (Wang *et al.,* 2024).

Flotation is the principal option for fine and altered ilmenite, but its success depends on matching reagent chemistry to the gangue assemblage (Wang *et al.,* 2024). A dithiocarbamate–hydroxamate collector achieved 94.2% recovery at pH 8, exceeding sodium oleate by approximately 35.8% through stronger surface adsorption (Qi *et al.,* 2024). A mixed sodium oleate–cetyltrimethylammonium bromide system recovered more than 98% of the ilmenite while limiting titanaugite recovery to below 25% (Yaun *et al.,* 2024). These improvements arise from different chemical mechanisms. Ferrate activation accelerates collector adsorption (Liao *et al.,* 2022), whereas 2-amino-1,3-propanediol and sodium citrate depress titanaugite through preferential interaction with gangue surfaces (Dai *et al.,* 2024; Yuan *et al.,* 2021). Sodium silicate reduces the co-aggregation of fine titanaugite and ilmenite through selective dispersion (Yuan *et al.,* 2025). Microwave pretreatment combined with copper-ion activation also improves flotation by producing surface microcracks and

modifying adsorption behaviour (Yang *et al.,* 2025; Wang *et al.,* 2024). Collectively, these findings show that reagent dosage cannot compensate for inadequate characterisation of the target mineral and gangue surfaces.

Hydrometallurgical and mechanochemical treatments become relevant when physical and flotation stages cannot attain the required TiO_2 grade. Controlled precipitation can separate iron and titanium from leach solutions (Purcell *et al.,* 2020), while acid leaching and pretreatment provide routes for producing TiO_2-rich material from complex concentrates (Nguyen & Lee, 2018; Tahooni *et al.,* 2025). Ball-milling-induced sulphurisation followed by carbothermic reduction initiates ilmenite-to-rutile conversion at an ilmenite-to-additive ratio of 4:1 (Wickramarachchi, 2021). These treatments do not replace beneficiation; they upgrade concentrates that remain below market specification after physical separation. Ultrafine particles below approximately 20 μm remain difficult to recover at acceptable grade and recovery using any single operation (Motovilov *et al.,* 2026). Selective flocculation and hybrid flowsheets address this limitation by assigning different gangue fractions to successive separation stages. The commercial sequence of low-intensity magnetic separation for magnetite removal, high-intensity magnetic separation for ilmenite pre-concentration, and flotation cleaning reflects this principle and has become established for increasingly lean and complex Chinese ores (Wang *et al.,* 2024). Sensor-based X-ray transmission and X-ray fluorescence sorting can strengthen these circuits by rejecting coarse waste before energy-intensive grinding (Robben & Wotruba, 2019; Peukert *et al.,* 2022; Luo *et al.,* 2022; Santos *et al.,* 2025).

Beneficiation performance also affects downstream smelting. Pelletisation trials on Panzhihua concentrate reduced electricity consumption from 2,546.5 to 2,218.9 kWh per tonne of slag (Song *et al.,* 2025). Sodium carbonate fluxing similarly lowers smelting temperature and melt viscosity for Satpaevsk ilmenite, while furnace modelling supports improved process productivity (Cui *et al.,* 2023; Myrzakulov *et al.,* 2024). Accessory rare-earth minerals may provide additional value, although their routine recovery from heavy-mineral-sand circuits' remains limited (Abaka-Wood *et al.,* 2022; Abbadi & Mucsi, 2024; Sampath *et al.,* 2023).

Table 4 compares the mineralogical operating windows, performance ranges, and limitations of the main beneficiation routes. The comparison confirms that hybrid flowsheets provide the most reliable balance between grade and recovery for fine, altered, and mineralogically complex ores.

Table 4. Comparative performance of beneficiation technologies for low-grade ilmenite

Technology	**Suitable ore characteristics**	**Typical recovery**	**Typical TiO_2 grade**	**TRL**	**Main advantage**	**Main limitation**	**Development potential**
Gravity separation	Coarse, liberated particles above 50–10	Low when used alone on fine ore	Low without downstream cleaning	9	Low cost and no reagent demand	Recovery declines below approximatel	Roughing before magnetic separation or flotation (Liu *et al.,* 2024;

	0 µm					y 30 – 50 µm (Motovilov *et al.*, 2026)	Raghupatruni & Satya, 2024)
HGMS and centrifugal HGMS	Fine ilmenite associated with weakly magnetic gangue	54 – 81% (Liu *et al.*, 2025; Zhang *et al.*, 2024)	13 – 32% (Ahmed *et al.*, 2024; Zhang *et al.*, 2024)	8 – 9	Recovers relatively fine particles	Grade plateaus where weakly magnetic gangue is abundant (Hu *et al.*	Full-scale centrifugal HGMS and coupling with reflux classification (Zhang *et al.*, 2024; Liu *et al.*, 2025)

						, 2023)	
Electrostatic separation	Dry, coarse, and well-liberated feed	High for suitable coarse fed	High for conductive fractions (Elder & Yan, 2003)	9	High selectivity without water	Sensitive to moisture and fines (Elder & Yan, 2003)	Limited role for fine or weathered ore as flotation expands (Wang *et al.*, 2024)
Flotation	Fine-grained, altered ore with complex gangue	Up to approximately 98% with mixed collector	Feed-dependent; suitable for final upgrad	9	Effective below 45 µm	Reagent demand and deposit-specific surface ch	Greener collectors, selective depressants, and microwave activation (Chen *et al.*,

		s (Yaun *et al.*, 2024)	ing			emistry	2024; Yang *et al.,* 2025)
Sensor-based sorting	Coarse particles suitable for waste rejection before comminution	Typical mass rejection of 30–50 %	Depends on feed and sensor response	7–8	Dry pre-concentration with low water demand	Requires coarse liberation and has limited effectiveness on fine or altered material	Multi-sensor fusion for heterogeneous ores (Adewuyi *et al.,* 2025; Luo *et al.,* 2022)
Hybrid flowsheets	Fine, altered, and mineralogically complex ore	Highest among available routes (Wang *et al.*, 2024)	Can attain commercial specifications	9	Balances recovery and concentrate grade	Higher capital and circuit complexity	Industrial benchmark for integrating emerging technologies

3.2 Emerging Beneficiation Technologies

Sensor-based sorting has the clearest route to industrial adoption because it can be installed before comminution without replacing established downstream circuits. Early waste rejection reduces grinding energy and water demand, but single-sensor systems struggle with heterogeneous particles (Robben & Wotruba, 2019; Peukert *et al.,* 2022; Luo *et al.,* 2022). This limitation is pronounced in altered ilmenite, where unaltered ilmenite, pseudorutile, and leucoxene may occur within the same particle (Pownceby *et al.,* 2008). The mineralogical variability reported for Egyptian and Brazilian deposits confirms why a single sensing modality may be insufficient (Moustafa, 2023; Wust *et al.,* 2024). Machine-learning-based fusion of multiple sensor and imaging signals offers a more suitable approach, although it remains at an early stage of integration

(Adewuyi *et al.,* 2025). Sensor sorting can reduce the mass entering the plant but cannot replace flotation for fine-particle separation (Santos *et al.,* 2025).

Microwave pretreatment and high-voltage pulse fragmentation target the energy-intensive liberation stage. Microwave effectiveness depends on dielectric contrast between ilmenite and gangue, making the response strongly ore-specific (Chen *et al.,* 2024). Microwave treatment with copper-ion activation produced 93.7% flotation recovery (Yang *et al.,* 2025), while combined washing, microwave, and ultrasonic treatment improved separation in related gangue systems (Xia *et al.,* 2024). Microwave heating has also cleaned magnetic products from beach-placer processing (Raghupatruni & Satya, 2024).

High-voltage pulse fragmentation produced a concentrate quality of 61.76% at 83.26% recovery under optimised conditions of 90 pulses, 35 kV, and 9 min. Modified electrode design improved selectivity further (Huang & Shi, 2018; Lay *et al.,* 2023). However, most evidence comes from base-metal and phosphate ores. Its applicability to ilmenite therefore remains inferred rather than demonstrated. Microwave and pulse fragmentation both offer selective breakage and lower downstream grinding demand, but capital cost, mineralogical sensitivity, and limited industrial validation constrain their adoption (Chen *et al.,* 2024; Lay *et al.,* 2023).

Ultrasound has stronger evidence as a leaching intensification method than as a physical beneficiation technology. Treatment at 800 W for 5 min reduced the required sulfuric acid concentration from 84% to 80%, increased titanium leaching efficiency from 87.71% to 93.07%, and saved 404 kg of acid per tonne of product (Moustafa, 2023). Combining microwave and ultrasound treatment increased leaching efficiency by a further 7.34% relative to ultrasound alone (Liu *et al.,* 2026). These reductions are environmentally relevant because sulfate and chloride TiO_2 production remain dominated by resource consumption and toxicity burdens. The sulfate route has a higher non-renewable resource demand despite having a warming potential comparable to that of the chloride route (Dai *et al.,* 2024), consistent with earlier life-cycle evidence for ilmenite and rutile mineral-sands processing (Farjana *et al.,* 2021). Whether ultrasound can provide similar benefits during upstream physical beneficiation remains uncertain.

Green flotation reagents offer a nearer-term improvement because they can be introduced without major equipment changes. Sodium alginate selectively depresses forsterite through strong bonding with magnesium sites while interacting only weakly with titanium sites on ilmenite. Its separation performance is comparable to that of synthetic depressants but with a lower toxicity concern. Related depressants developed for ilmenite–titanaugite separation support the technical feasibility of reagent substitution (Dai *et al.,* 2024; Yuan *et al.,* 2021). Commercial use will depend more on reagent availability, consistency, and plant qualification than on new capital investment.

Dry beneficiation and bio-beneficiation remain less developed for fine, altered ilmenite. Dry magnetic and electrostatic separation are already mature for coarse mineral sands; the unresolved challenge is extending them to fine fractions currently treated by flotation (Elder & Yan, 2003; Gupta & Yan, 2016). Bioleaching has produced weak results. Iron-oxidising and iron-scavenging bacteria achieved little iron or titanium dissolution from ilmenite and basalt, even after extended treatment (Nguyen & Lee, 2018). This evidence indicates limited current effectiveness rather than merely insufficient research.

The barriers to adoption are technology-specific (Wills & Finch, 2015). Sensor sorting is constrained mainly by algorithmic integration and heterogeneous feed response (Peukert *et al.,* 2022; Luo *et al.,* 2022). Microwave treatment and high-voltage pulse fragmentation face ore-specific performance and capital-cost

risks (Chen *et al.,* 2024; Huang & Shi, 2018). Ultrasound must progress from batch experiments to continuous industrial throughput (Liu *et al.,* 2026). Green reagents face comparatively low technical barriers but require supply-chain and process qualification. Sensor sorting and green reagent substitution are therefore the most plausible near-term options because both can be integrated into existing plants (Peukert *et al.,* 2022).

No technology performs best across every mineralogical condition. Gravity concentration is economical for coarse placer material but loses effectiveness below approximately 50 μm (Motovilov *et al.,* 2026). Magnetic separation treats finer material but cannot readily distinguish ilmenite from gangue with overlapping susceptibility (Hu *et al.,* 2023). Electrostatic separation requires a dry, liberated feed that altered ores rarely provide (Elder & Yan, 2003). Flotation remains the most effective option for fine and chemically complex particles, supporting the industrial preference for hybrid low-intensity magnetic separation, high-intensity magnetic separation, and flotation circuits (Wang *et al.,* 2024; Yaun *et al.,* 2024).

Among emerging approaches, microwave-assisted leaching and less toxic reagents have the strongest near-term evidence (Liu *et al.*, 2026). Sensor sorting offers the clearest integration pathway (Peukert *et al.*, 2022; Luo *et al.*, 2022), while microwave and high-voltage pulse pretreatment remain ore-specific and insufficiently validated for industrial ilmenite processing (Chen *et al.*, 2024; Huang & Shi, 2018). Bio-beneficiation has not yet demonstrated adequate extraction. Future flowsheets should therefore be selected from measured alteration, liberation, magnetic susceptibility, dielectric response, and surface chemistry rather than transferred unchanged between deposits (Pownceby *et al.*, 2008; Bulatovic, 2010).

4. MULTI-PRODUCT PROCESS INTEGRATION

Low-grade ilmenite is commonly processed as a feedstock for pigment-grade TiO_2 or titanium sponge (Maldybayev *et al.,* 2024). This single-product model overlooks iron, vanadium, chromium, scandium, REEs, and silicate-rich residues generated during upgrading. Recovering these streams as products can improve project economics, reduce waste liabilities, and support the treatment of ilmenite as a multi-element resource.

4.1 Sustainable Pyrometallurgy

Conventional EAF smelting retains approximately 10–12 mass% FeO in the slag to maintain fluidity, limiting TiO_2 enrichment and increasing energy demand (Pistorius, 2008; Lv *et al.,* 2017). Pre-reduction improves furnace stability and reduces smelting energy, while hydrogen and hydrogen-enriched syngas offer faster kinetics and lower direct emissions than carbon-based reduction (Nayak *et al.,* 2025). Reaction behaviour remains sensitive to additives and operating conditions. Na_2CO_3 changes both activation energy and the governing mechanism (Li *et al.,* 2024), while studies on Panzhihua ilmenite show that the rate-controlling step changes with conversion (Gou *et al.,* 2017). Differences among solid-state, smelting, non-pre-oxidised, and vacuum carbothermic routes also influence reactor and product selection (Huang *et al.,* 2012; Bhalla *et al.,* 2017; Zhang *et al.,* 2017).

Hydrogen plasma smelting reduction converted approximately 70% of iron oxides to metallic iron with 92.31 wt.% purity. The resulting titania-enriched slag contained 6.84 wt.% oxygen and 0.37 wt.% silicon (Sun *et al.,* 2025). Although the process replaces CO_2 with water as the principal reaction product, its performance and economics on variable raw ores remain unresolved. CO_2/CH_4 plasma can reuse greenhouse gases as reaction media, but the reported reduction was incomplete (El Khalloufi *et al.,* 2024). Non-plasma hydrogen reduction is closer to application. Panzhihua ilmenite

achieved 87.5% metallisation at 1150°C after 80 min, with diffusion control and an activation energy of approximately 89 kJ/mol (Si *et al.,* 2012). Optimisation studies on Kahnuj ilmenite and green-rutile production from secondary ilmenite support further development (Ghasemi *et al.,* 2024; Spencer *et al.,* 2025). Pre-oxidation accelerates reduction by producing a porous hematite–rutile structure (Lv *et al.,* 2017; Zhang *et al.,* 2022). Temperature, steam content, and titanium suboxide formation then govern the transition from ferric-to-ferrous conversion to metallisation (Canaguier & Ringdalen, 2023; Yu *et al.,* 2023).

Metallic iron provides an important revenue stream, but hydrogen-based processing remains sensitive to hydrogen price and electricity carbon intensity. Its viability must therefore be assessed using the combined value of iron and titania slag.

4.2 Eco-Friendly Hydrometallurgy

Leaching performance depends on mineralogy and pretreatment rather than acid type alone (Thambiliyagodage *et al.,* 2021; Tahooni *et al.,* 2025). Adding $CaCl_2$ to HCl increased titanium and iron extraction from 87% and 93% to 96% and 97%, respectively, by raising the effective chloride concentration (Das *et al.,* 2013). Iron-assisted HCl leaching extracted approximately 92% Fe from South African ilmenite through diffusion-controlled kinetics (Daba *et al.,* 2022). Indonesian ilmenite also showed positive responses to acid concentration and time, but a negative temperature effect within the investigated range (Supriyatna *et al.,* 2024).

Sulfate leaching is more established but produces greater acidic waste. Under reducing conditions, dissolution depends on surface reaction and the Fe(III)/Fe(II) ratio, making reductant addition a kinetic control rather than merely a purification step (Zhang & Nicol, 2010). An alkaline alternative combines NaOH roasting, leaching, solvent extraction, hydrolysis, and calcination to produce high-purity pigment without the combustion-related CO_2 of chloride processing (Middlemas *et al.,* 2013).

KOH decomposition improves ilmenite solubility by forming potassium titanate (Nayl *et al.,* 2009). Mechanical activation converts pseudorutile into rutile and pseudobrookite, although conventional kinetic models become unreliable above approximately 85 wt.% H_2SO_4 (Dubenko *et al.,* 2020). A hydrophobic deep eutectic solvent has also selectively recovered Ti(IV) from HCl leachate with lower toxicity than conventional solvents (Zhu *et al.,* 2025). Sustainable hydrometallurgy must combine selective extraction with acid regeneration and co-product recovery.

4.3 Direct Synthetic Rutile Production

The Becher, Benelite, and Murso processes target approximately 90–95% TiO_2 but were developed for relatively clean, weathered feeds (Kurniawan *et al.,* 2022). Their slow iron-removal kinetics increase reactor size and cost when altered low-grade ores are processed. Weak ferric-sulfate leaching removes iron in 2–3 h, compared with about 22 h for Becher aeration (Xiang *et al.,* 2020). HCl–$CaCl_2$ solutions at approximately 500 g/L also improve selectivity across ilmenite and pseudorutile phases (Das *et al.,* 2013).

Becher-route synthetic rutile has been used to produce low-oxygen titanium alloy electrochemically (Benson *et al.,* 2016). Thermal reduction followed by magnetic separation provides an acid-free route but requires higher temperatures (Zhu *et al.,* 2025). Replacing coal with charcoal or biofuel can improve metallisation and rutile grade while producing activated carbon as a co-product (Spencer *et al.,* 2022). Such modifications reduce emissions without replacing the established flowsheet.

4.4 Resource Recovery Beyond Titanium

Iron. Smelting produces marketable pig iron, whereas synthetic-rutile routes often generate fine iron residues that are difficult to commercialise (Filippou & Hudon, 2009). Processing choice

therefore determines whether iron becomes revenue or waste.

Vanadium. Integrated vanadium–steel processes account for approximately 73% of global output. Demand is reported to be growing by about 2.7% annually in steel and 6% in energy-storage applications (Nkosi *et al.,* 2026). Slag-based recovery can be economically viable, although silica, phosphorus, and chromium co-extraction continues to limit roasting–leaching selectivity (Gilligan & Nikoloski, 2020; Lee *et al.,* 2021; Nkosi *et al.,* 2026).

Chromium. Similar physical properties limit chromite–ilmenite separation. Reduction smelting of Obukhovskoye concentrate transfers iron and chromium into ferrochrome-feed metal while retaining titanium in the slag. Associated monazite also indicates REE potential (Kenzhaliyev *et al.,* 2024). Gravity recovery loses efficiency at fine sizes (Murthy *et al.,* 2011), while ferrochrome production remains carbon-intensive despite advances in pre-reduction, oxidative pelletising, and plasma processing (du Preez *et al.,* 2023).

Rare earth elements and thorium. Monazite associated with heavy-mineral sands provides a potential REE stream (Mudd & Jowitt, 2016). Its physical separation can be incorporated into existing ilmenite, zircon, and rutile circuits (Jordens *et al.,* 2013), with plant recoveries of 50–80% reported (McNulty *et al.,* 2022). Thorium commonly occurs at single-digit weight percentages and imposes radiological and residue-management requirements that may outweigh REE revenues (IAEA, 2020).

Scandium. Sulfate-process spent acid may contain scandium at tens of milligrams per litre. Because this stream already requires treatment, recoveries above 95% through solvent extraction can convert part of the treatment cost into revenue (Wang *et al.,* 2011; Li *et al.,* 2018). Pilot-scale nanofiltration, solvent extraction, and crystallisation systems are advancing this route toward engineering application (Hedwig *et al.,* 2022).

4.5 Tailings and Slag Valorisation

Titanium slags and leach residues contain silicate and aluminosilicate phases suitable for geopolymer production, although activator demand, transport distance, and embodied energy affect environmental performance (Asim *et al.,* 2026). Titanium-specific evidence remains limited compared with fly-ash and blast-furnace-slag systems. However, backfill binders containing residual slag, titanium gypsum, and tailings developed strength through ettringite and calcium silicate hydrate formation (Li *et al.,* 2024). Adding titanium tailing slag to CaO–steel-slag paste increased early strength by more than an order of magnitude through calcite, calcium silicate hydrate, and hydrocalumite formation (Tang *et al.,* 2023).

Multi-product integration distributes costs and environmental burdens across titania, iron, critical metals, and construction materials. It can reduce residual waste, but each product must satisfy technical, environmental, and regulatory requirements. Low-grade ilmenite viability therefore depends on the combined value and marketability of all recovered streams, not titanium margin alone.

5. QUANTITATIVE SUSTAINABILITY ASSESSMENT

Recovery and concentrate grade alone cannot establish whether low-grade ilmenite processing is sustainable. Beneficiation, chemical upgrading, reagent regeneration, and residue management impose cumulative energy, water, carbon, and economic burdens that are often obscured when each stage is assessed separately. A credible comparison must therefore integrate specific energy consumption (SEC), water use, life-cycle impacts, exergy efficiency, techno-economics, and multi-criteria decision analysis (MCDA).

5.1 Energy Consumption per Tonne of TiO_2-Equivalent Product

Energy demand is governed by comminution, separation, reduction, and reagent recovery. Physical beneficiation generally has the lowest energy requirement (Zhai *et al.,* 2020), but this advantage declines as mineral dissemination falls below 38 μm. Hard-rock titanomagnetite has a typical Bond Work Index of 14–19 kWh/t, and the energy required for liberation rises non-linearly at finer sizes. High-pressure grinding rolls installed before ball milling can reduce this demand, although fine flotation still carries the combined energy burden of grinding and reagent production (Baawuah *et al.,* 2020).

Chemical upgrading is more energy-intensive. EAF smelting at 1500–1650°C produces titania slag containing 75–85% TiO_2 and pig iron but requires substantial electrical and thermal input (Pistorius, 2008). Becher-route synthetic rutile is dominated by fossil-fuel consumption in the reduction kiln (Middlemas *et al.,* 2015), while hydrometallurgical routes require energy for pyrohydrolysis, acid concentration, and distillation. Reported SEC values therefore depend on the feed Fe:Ti ratio, liberation size, energy source, process boundary, and co-product allocation. Waste-heat recovery from EAF off-gas can lower net energy demand. System expansion can also improve the apparent performance of pyrometallurgy by crediting pig iron and V_2O_5 that displace primary production. Under such boundaries, an integrated smelting route may perform better than standalone hydrometallurgy despite its higher direct energy consumption

5.2 Water Footprint and Hydrological Dynamics

Water demand reflects a trade-off between process efficiency and resource conservation. Dry beneficiation requires little water beyond dust suppression but performs poorly on particles below approximately 75 μm. Wet flotation recovers finer material but consumes more water, while collectors and frothers progressively degrade the quality of recycled process water (Zhai *et al.,* 2020). Hydrometallurgical and synthetic-rutile routes generally have the highest freshwater requirements, with wet circuits consuming substantially more water per unit of concentrate than dry configurations (Farjana *et al.,* 2021).

Effluent composition is as important as withdrawal volume. HCl leaching produces acidic solutions containing $FeCl_2$, Al^{3+}, and Mg^{2+}. Without acid recovery, lime neutralisation converts these streams into large volumes of gypsum- and iron-rich sludge. Closed-loop circuits and membrane filtration can raise water recycling above 90–95%. Zero-liquid-discharge (ZLD) systems can eliminate aqueous discharge, but evaporation and concentration impose a substantial energy penalty (Tong & Elimelech, 2016). This trade-off may still be acceptable in water-scarce regions where freshwater access and discharge permits determine operational viability.

5.3 Carbon Emissions and Decarbonisation Pathways

Cradle-to-gate emissions arise from process reactions, electricity supply, and embodied burdens in reagents and consumables. Grid electricity contributes Scope 2 emissions, while acids, grinding media, and other consumables add Scope 3 burdens. The sulfate process has a particularly high footprint because of the energy required for acid concentration and the embodied carbon of H_2SO_4 production (Middlemas *et al.,* 2015).

When renewable electricity supplies hydrogen production and the EAF, this route can eliminate direct process-carbon emissions (Van Kaam *et al.,* 2025). Na_2CO_3 addition accelerates reduction and promotes iron-particle agglomeration (Lv *et al.,* 2022). Biochar offers another pathway by replacing fossil carbon with biogenic carbon, although its lower mechanical strength and higher alkali content may require furnace modification (Malatji *et al.,* 2024). Carbon reduction alone does not establish environmental superiority. Hydrometallurgical cleanup may lower greenhouse gas emissions

while increasing acidification, aquatic toxicity, and wastewater burdens.

5.4 Exergy Efficiency

First-law analysis measures energy quantity but does not capture losses in energy quality or chemical potential. Exergy efficiency provides a more complete measure. When both physical and chemical exergy are considered, carbothermic smelting can outperform unintegrated hydrometallurgy because dissolution, neutralisation, and precipitation destroy chemical exergy irreversibly (Van Schaik & Reuter, 2013). Heat-recovery steam generation and dry slag granulation can recover part of the exergy otherwise lost during smelting. Selective chlorination of titania slag reduces destruction further by using lower-temperature gas‑solid conversion (Kang & Okabe, 2014).

5.5 LCA and Allocation Methodology

Low-grade hard-rock ores generally produce higher global warming potential (GWP), acidification potential (AP), and abiotic depletion potential (ADP) per tonne mined than high-grade placers because they require finer grinding and more reagents (Norgate & Haque, 2010; Middlemas *et al.,* 2015). However, the reported burden depends strongly on how impacts are allocated among titanium, iron, vanadium, and other products. Mass allocation assigns a large share of the burden to the high-volume iron product and may understate the footprint of TiO_2. Economic allocation produces the opposite effect because titanium products have greater unit value (Norgate & Haque, 2010). System expansion instead credits the process for avoiding primary production, such as pig iron from blast furnaces or V_2O_5 from primary ores. These displacement credits can make integrated low-grade processing environmentally preferable. Cross-study comparisons are therefore unreliable unless they use consistent functional units, system boundaries, allocation rules, and co-product assumptions.

5.6 Techno-Economic Assessment

Low-grade feed increases equipment capacity, energy consumption, reagent demand, and residue handling, often making standalone TiO_2 production uneconomic. Co-product recovery changes this relationship. Integrated resource models show that V_2O_5, Sc_2O_3, REEs, Cr_2O_3, and $ZrSiO_4$ can increase project returns substantially (Gilligan & Nikoloski, 2020). Pig-iron revenue strengthens smelting economics (Jiao *et al.,* 2018), while vanadium recovery and scandium extraction from spent acid convert residues into saleable products (Gilligan & Nikoloski, 2020; Qiu *et al.,* 2019).

As shown in Table 5, multi-resource processing requires greater capital and operating expenditure than a single-product route. However, projected co-product revenue changes the net margin from approximately −$150 to +$50/t to +$250‑650/t. The corresponding payback period falls by about 60%, while the internal rate of return rises from 3.2‑6.5% to 18.5‑27.2%. Valorising slag and gangue as cementitious materials or aggregates may provide further savings by reducing long-term tailings liabilities.

Table 5. Indicative techno-economic comparison of single-product and integrated low-grade ilmenite processing

Metric	**Single-product route**	**Integrated multi-resource route**	**Difference**
CAPEX	$550–850/t	$850–1,400/t	+54.5%
OPEX	$750–1,100/t	$800–1,250/t	+11.8%
Co-product revenue	$0/t	$450–1,100/t	New revenue stream
Net margin	−$150 to +$50/t	+$250 to +$650/t	Deficit to surplus

Payback period	12.5–16.0 years	3.8–5.5 years	Ap-proxi-mately 60% shorter
Internal rate of return	3.2–6.5%	18.5–27.2%	+19.0 percent-age points

5.7 Multi-Criteria Decision Analysis

No route performs best across all environmental, technical, and economic criteria. MCDA methods such as the analytical hierarchy process, TOPSIS, and PROMETHEE make these trade-offs explicit by converting weighted criteria into comparative rankings (Mutambo *et al.,* 2022). When decarbonisation receives the highest weighting, hydrogen direct reduction combined with EAF smelting and acid recycling ranks first, with a closeness coefficient of (C^=0.88). When capital efficiency and technical risk dominate, conventional wet high-intensity magnetic separation (WHIMS), flotation, and coal-fired EAF smelting rank highest at (C^=0.82), reflecting their technology-readiness level of 9.

Balanced weighting favours an integrated closed-loop route comprising fine grinding, WHIMS‑flotation, pre-reduction, selective vanadium and scandium leaching, ZLD water treatment, and slag geopolymerisation. This configuration produces the highest overall score, (C^*=0.91), because it balances recovery, emissions, water use, co-product value, and technical maturity. The ranking is nevertheless sensitive to regional electricity supply, water scarcity, carbon pricing, and the assigned value of co-products.

5.8 Integrated Sustainability Synthesis

Assessing individual operations in isolation can reverse the apparent sustainability ranking of complete processing routes. Hydrometallurgical leaching performs poorly when acid consumption, water use, and neutralisation are considered alone. Its performance improves when acid regeneration, mechanical vapour recompression, water recycling, and selective vanadium or scandium recovery are incorporated. Similarly, magnetisation roasting followed by staged separation can improve recovery from mineralogically complex ores (Sun *et al.,* 2020).

Table 6 shows that physical beneficiation has the lowest direct energy, water, and carbon burdens but cannot recover finely disseminated ilmenite efficiently. Flotation improves fine-particle recovery at the cost of greater reagent and wastewater burdens. Coal smelting and sulfate processing are commercially mature but carbon- and resource-intensive. Hydrogen reduction and integrated multi-resource processing offer the lowest net impacts, although both require higher capital investment and further industrial validation. Sustainable route selection must therefore consider the complete flowsheet, including co-products, recycled utilities, avoided primary production, and residual waste.

Table 6. Comparative sustainability performance of low-grade ilmenite beneficiation and resource-recovery technologies

Technology	**Route**	**TiO_2 recovery (%)**	**Co-products**	**Energy (GJ/t)**	**Water (m^3/t)**	**Carbon (tCO_2-eq/t)**	**Exergy efficiency (%)**	**LCA performance**	**OPEX**	**TRL**	**Circularity**	**Principal advantage**	**Main limitation**
Phy	Gra	65–68	Mag	0.5	0.2	0.0	68–72	Low	Low	9	Low	Sim	Poo

sical beneficiation	vity–WHIMS–electrostatic separation	82	netite, zircon	–2.5	–2.5	5–0.25	78	GWP and AP; high land use			–medium	pleandreagent-free	recovery below 38 µm
Froth flotation	Stirred milling and flotation	72–88	Apatite, magnetite	3.5–6.0	4.0–12.0	0.35–0.75	45–58	Moderate ecotoxicity	Medium	8–9	Medium	High fine-particle recovery	Reagent and wastewater burdens
Coal-redu	Pre-reduc	85–94	Pigiron	12.0–22.0	2.0–6.0	2.80–4.50	38–52	High GWP	Medium–hi	9	Medium	Commercia	High carbo

ctionsmelting	tionandEAF								gh			lmaturity	nintensity
Beche rsynthetic rutile	Kiln, aeration, and leaching	80–90	Fe_2O_3, ammonium salts	150.0–250.0	80.0–180.0	2.50–4.20	30–42	High GWP and AP	Medium–high	9	Medium–low	Produces premium rutile above 92% TiO_2	High thermal demand
Sulfate leaching	H_2SO_4 leaching and hyd	78–88	Copperas, vanadium sl	250.0–400.0	30.0–65.0	3.20–5.50	22–32	Severe AP, EP, and HTP	High	9	Low	Accepts low-grade fe	Large acidic-effluent

	rolysis		udge									ed	burden
Direct HCl leaching	HCl leaching and pyrohydrolysis	82–93	Synthetic hematite, recycled HCl	20.0–350	3.0–80	2.20–3.80	28–38	Moderate GWP	High	6–7	Medium–high	Allows acid recovery	Thermal demand and corrosion
Hydrogen reduction and EAF	Hydrogen direct reduction and green	88–95	Low-carbon pig iron	10.0–160	1.5–4.0	0.40–1.20	48–62	Very low GWP	High	4–5	High	Very low direct carbon emissions	Green-hydrogen cost and low TRL

	EAF													
Integrated multi-resource route	WHIMS, flotation, leaching, and ZLD	88–96	Pig iron, V_2O_5, Sc_2O_3, REEs, geopolymers	12.0–18.0	1.2–3.0	0.30–0.90	52–64	Low net impact	Medium	4–6	Very high	High resource efficiency	High CAPEX and process complexity

6. CURRENT CHALLENGES AND KNOWLEDGE GAPS

Industrial deployment of low-grade ilmenite technologies is constrained by interconnected technical, environmental, economic, and regulatory barriers. Mineralogical complexity increases energy and reagent demand, which affects life-cycle performance, project economics, and regulatory approval. These interactions explain why promising laboratory results often fail to progress beyond pilot scale.

6.1 Technical Challenges

Mineralogical heterogeneity limits the transferability of beneficiation flowsheets. Magmatic, placer, and weathered deposits differ in liberation behaviour, gangue association, alteration, and surface chemistry. A process optimised for one

deposit may therefore perform poorly on another (Zhai *et al.,* 2020; Wang *et al.,* 2024; Nzeh & Popoola, 2024). Flowsheet design remains largely empirical because predictive models linking ore texture, alteration index, grain size, and comminution response are underdeveloped. Each deposit consequently requires extensive test work, increasing development costs and delaying investment.

Automated mineralogy using QEMSCAN or mineral liberation analysis should be integrated with machine-learning models that predict separation performance from ore texture. Such models could reduce experimental requirements and support feed-responsive process control.

Scale-up presents a related challenge. Hydrogen plasma smelting reduction, microwave pretreatment, and sensor-based sorting have produced promising laboratory or pilot results but remain mainly at technology-readiness levels 4‑6 (Torres-Mejia *et al.,* 2026; Adewuyi *et al.,* 2025). Capital risk and feed-specific optimisation favour established coal reduction and sulfate leaching, despite their greater environmental burdens. Demonstration-scale trials must therefore use variable industrial feeds rather than controlled laboratory material. Standardised technology-readiness reporting would also improve comparison across emerging routes.

6.2 Environmental Challenges

Commercial hydrometallurgical routes generate substantial acidic residues, tailings, and wastewater. The sulfate process alone produces approximately one million tonnes of ilmenite mud annually (Chyliński *et al.,* 2020; TahooniBonab *et al.,* 2025). Sulfate and chloride leaching remain commercially important because they can process complex low-grade feeds, but their waste burdens create land-use conflicts, permitting delays, and long-term liabilities, particularly in water-scarce regions.

Closed-loop acid regeneration and zero-liquid-discharge systems can reduce these burdens. Residues may also be converted into cementitious additives or geopolymer feedstocks. However, technical feasibility has not yet translated into certified products or stable markets. Long-term durability, contaminant leaching, and compliance with construction standards require further validation.

Environmental comparisons are also weakened by inconsistent LCA methods. Functional units, system boundaries, and co-product allocation can change the reported carbon footprint of the same process several-fold (Norgate & Haque, 2010; Dai *et al.,* 2024). Plant-level inventory data are rarely available for independent verification. The sector therefore needs ISO-aligned assessment protocols and third-party-verified inventory databases covering beneficiation, upgrading, co-product recovery, and residue management.

6.3 Economic Challenges

Standalone titanium recovery from low-grade ilmenite is often uneconomic, making project viability dependent on vanadium, scandium, and REE co-recovery (Gilligan & Nikoloski, 2020). These co-products can improve margins but introduce price risk because their markets are smaller and less transparent than the TiO_2 pigment market. Feasibility studies may therefore depend on uncertain long-term revenue assumptions, increasing financing costs for integrated projects.

More reliable price-discovery mechanisms and standardised reporting of co-recoverable resources would reduce this uncertainty. Blended-finance mechanisms may also be needed for first-of-kind plants, where technical and market risks exceed those of established single-product operations.

Published cost estimates provide another weak basis for investment decisions. Many CAPEX and OPEX values originate from individual studies or vendor projections rather than independent operating data from multiple plants (Mutambo *et al.,* 2022). Commercial confidentiality further restricts validation. Pooled and anonymised industry

databases, combined with open techno-economic models and sensitivity analysis, would provide more defensible cost ranges than single-point estimates.

6.4 Policy and Regulatory Challenges

Residue-valorisation technologies can be technically viable yet commercially unusable because end-of-waste criteria and secondary-material standards remain incomplete. In Europe, unresolved chemical-risk requirements, outdated product standards, and absent end-of-waste criteria can delay the market entry of mineral-derived products for decades (Armistead & Babaahmadi, 2025). Similar regulatory fragmentation affects circular practices across the mining sector (Cotrina-Teatino & Marquina-Araujo, 2025). Purpose-specific residue criteria, streamlined risk assessment, and supervised regulatory pilot programmes are needed to connect technical validation with market approval.

Critical-mineral classification and legacy-waste liability also vary across jurisdictions. Titanium designation often reflects national supply-security priorities rather than resource geology alone (USGS, 2025). At the same time, companies reprocessing historical tailings may inherit liability for damage they did not cause, even when recovery would reduce the site's environmental risk (Podgorney *et al.,* 2025). This discourages the recovery of REEs, scandium, and vanadium from existing tailings. Safe-harbour provisions, coordinated critical-mineral policies, and streamlined brownfield permitting could reduce these barriers while preserving environmental accountability.

7. FUTURE RESEARCH DIRECTIONS

Future progress depends on integrating decarbonised chemistry, modular renewable-powered plants, intelligent process control, and multi-resource recovery. Evidence presented in the quantitative assessment shows that combined technologies provide greater environmental and economic benefits than isolated process improvements.

7.1 Decarbonised Reduction and Beneficiation Chemistry

Hydrogen reduction is the most promising route for reducing direct emissions from carbothermic and coal-based processing when hydrogen is produced using renewable electricity (Van Kaam *et al.,* 2025). Kinetic and metallisation studies on Panzhihua and Kahnuj ilmenite provide a foundation for further scale-up (Si *et al.,* 2012; Ghasemi *et al.,* 2024). Hydrogen plasma smelting reduction may combine rapid reduction with direct treatment of titania-rich feeds, but it remains at TRL 4–5 (Torres-Mejia *et al.,* 2026). Research should now move from further laboratory demonstrations to continuous operation using variable industrial feeds and electrolyser-scale hydrogen supply.

Decarbonisation must also extend beyond reduction. Replacing coal with biofuel in the Becher process improved metallisation and rutile grade while producing activated carbon as a co-product (Spencer *et al.,* 2022). Similar efforts should address electrified comminution and lower-temperature flotation systems. Hydrophobic deep eutectic solvents have already demonstrated selective, low-toxicity Ti(IV) recovery from ilmenite leachate (Zhu *et al.,* 2025). Their next development stage should examine continuous operation, solvent regeneration, and sequential recovery of vanadium, scandium, and REEs from a common leach solution. Methanesulfonic acid may also warrant ilmenite-specific testing, although its technical suitability has not yet been established.

7.2 Renewable-Powered Modular Plant Architectures

Many low-grade ilmenite resources are geographically dispersed or too small to justify conventional fixed concentrators. Modular and relocatable plants could reduce capital exposure and allow processing capacity to follow resource availability. Renewable hybrid microgrids have achieved more than 80% renewable penetration at isolated mine sites while

approaching the cost competitiveness of diesel systems (Roemer *et al.,* 2026).

Research should adapt WHIMS–flotation and pre-reduction circuits into standardised modules suitable for smaller deposits. Their performance must be tested under variable feed grades and mineralogy. Renewable systems must also accommodate the intermittent, high-torque demand of comminution without requiring uneconomic energy-storage capacity. Plant scale, power supply, comminution duty, and reduction route should therefore be optimised together rather than designed as separate systems.

7.3 Intelligent and Autonomous Process Systems

Digital process control offers a means of responding to the mineralogical variability that limits fixed ilmenite flowsheets. Neural-network digital twins have achieved more than 90% accuracy in estimating flotation states from combined industrial and simulated data (Hasidi *et al.,* 2024). Machine learning is also being applied to grinding, flotation, and roasting, with digital twins supporting predictive closed-loop control (Szmigiel *et al.,* 2024; Bai *et al.,* 2025).

Ilmenite-specific systems should integrate automated mineralogy, sensor sorting, and process data so that reagent dosage, magnetic field intensity, grinding conditions, and reduction temperature can respond to feed changes in real time (Adewuyi *et al.,* 2025). Sensor sorting, grade forecasting, and predictive control currently operate largely as separate tools. Integrating them into a single closed-loop system from ore sorting to concentrate production is the next research priority. Modular plants may provide a suitable demonstration platform because their smaller scale can make comprehensive instrumentation more manageable.

7.4 Integrated Beneficiation–Metallurgy and Critical-Metal Co-Recovery

Standalone titanium recovery from low-grade ilmenite is often economically marginal, whereas iron, vanadium, scandium, and REE recovery can improve margins and shorten payback periods (Gilligan & Nikoloski, 2020). Achieving these benefits requires beneficiation and metallurgy to be designed together. A flotation circuit optimised only for ilmenite grade may reject fractions containing economically recoverable scandium or REE minerals. Future flowsheets should therefore optimise titanium grade, recovery, co-product value, and environmental performance simultaneously.

Critical-metal recovery remains the least mature part of this integrated system. Scandium extraction from acidic waste has achieved high recoveries at laboratory and pilot scales, while REE-bearing accessory minerals occur in many ilmenite-hosting deposits (Morin-Ka *et al.,* 2025). However, routine industrial recovery remains uncommon. Research should develop sequential extraction systems capable of recovering several elements from a common leachate, including the deep eutectic solvents discussed in Section 7.1. MCDA should then compare alternative co-recovery configurations using economic, environmental, technical, and market-risk criteria rather than titanium recovery alone (Mutambo *et al.,* 2022). Pilot-scale mass balances are also needed because integrated multi-resource routes remain at TRL 4–6 and lack the operating data required for commercial investment.

Sustainable low-grade ilmenite utilisation is unlikely to result from a single technology. Its industrial viability will depend on coordinated development of low-carbon reduction, renewable modular infrastructure, mineralogy-responsive process control, and critical-metal recovery. These systems must be demonstrated together under realistic feed and operating conditions before their combined environmental and economic advantages can be established at commercial scale.

8. CONCLUSIONS

Sustainable utilisation of low-grade ilmenite depends on integrating mineralogical characterisation, beneficiation, metallurgical upgrading, co-product recovery, and residue management. No beneficiation technology performs best across all ore types. Gravity concentration remains economical for coarse, liberated placers but loses efficiency below approximately 50 μm. Magnetic separation treats finer material but cannot readily reject gangue with overlapping susceptibility, while electrostatic separation requires dry, well-liberated feed. Flotation is more effective for fine and altered ores, supporting the industrial preference for hybrid LIMS–HIMS–flotation circuits. Microwave-assisted treatment, less toxic reagents, and sensor sorting offer practical near-term improvements, whereas hydrogen reduction provides the strongest pathway for downstream decarbonisation. In each case, flowsheet selection must be based on deposit-specific mineralogical characteristics.

Co-product recovery can change the economics of low-grade resources. Estimated net margins increase from −$150 to +$50/t for standalone titanium production to $250–650/t when vanadium, scandium, and REEs are recovered. The corresponding internal rate of return rises from single-digit values to 18–27%, while payback falls by approximately 60%. Realising these gains requires beneficiation and metallurgy to be designed around titanium and associated elements from the outset.

Tailings, acidic mud, and slags can be converted into construction materials or sources of critical metals, but commercial adoption remains limited. Approximately one million tonnes of ilmenite mud are still stockpiled annually, reflecting the absence of harmonised end-of-waste criteria, product standards, and established residue markets. Near-term action should prioritise green reagents, biofuel reductants, sensor sorting, and routine scandium and vanadium recovery. Medium-term development should validate hydrogen reduction, green solvents, and digital-twin control while improving regulatory frameworks. The longer-term objective is a renewable-powered, autonomous processing system that recovers titanium, iron, critical metals, and usable residual materials within an integrated flowsheet.

Conflicts of interest

The authors declared that there is no conflict of interest.

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