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Hydrometallurgy of Tungsten from Primary Ores and Secondary Sources: Mineralogical Controls, Selective Recovery, Process Integration, and Sustainability—A Critical Review

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Abstract

Tungsten extraction involves a technically heterogeneous portfolio of scheelite, wolframite, mine wastes, cemented-carbide scrap, spent catalysts, and process residues. This critical review evaluates how feed mineralogy, aqueous speciation, reaction pathways, separation selectivity, and process integration control the conversion of these materials into marketable tungsten intermediates, notably ammonium paratungstate (APT). Literature assembled through 17 route-specific Boolean search strategies for 2020–2026, with selected expansion to 2010–2019, is appraised by feedstock, mechanism, impurity behavior, technological evidence, and environmental relevance. The synthesis identifies structural differences between alkaline digestion of wolframite, chemically assisted decomposition of scheelite, and secondary-material processing in which cobalt, vanadium, molybdenum, arsenic, and titanium influence the preferred flowsheet. In solution purification, W–Mo separation and changing polytungstate chemistry require explicit control of solution composition rather than generic extraction performance claims. Closed-loop reagent management, full metal balances, impurity deportment, product purity, residue stability, and pilot-scale demonstration remain essential but are reported inconsistently. This review proposes a process-selection framework that integrates mineralogical qualification, thermodynamic–kinetic interpretation, evidence-based separation screening, and coupled technical, economic, and environmental assessment. The review distinguishes established process principles from promising laboratory innovations and identifies minimum evidence needed before industrial extrapolation.

Keywords: Tungsten hydrometallurgy; Scheelite; Wolframite; Secondary resource recycling; Tungsten–molybdenum separation; Ammonium paratungstate

Highlights

- Mineralogy governs reaction chemistry and reagent demand across primary tungsten ores.
- Secondary tungsten streams require co-metal and impurity-specific circuit design.
- W–Mo separation and APT purity are pivotal downstream process bottlenecks.
- Industrial selection must reconcile selectivity, reagent recycling, residues, and scale.

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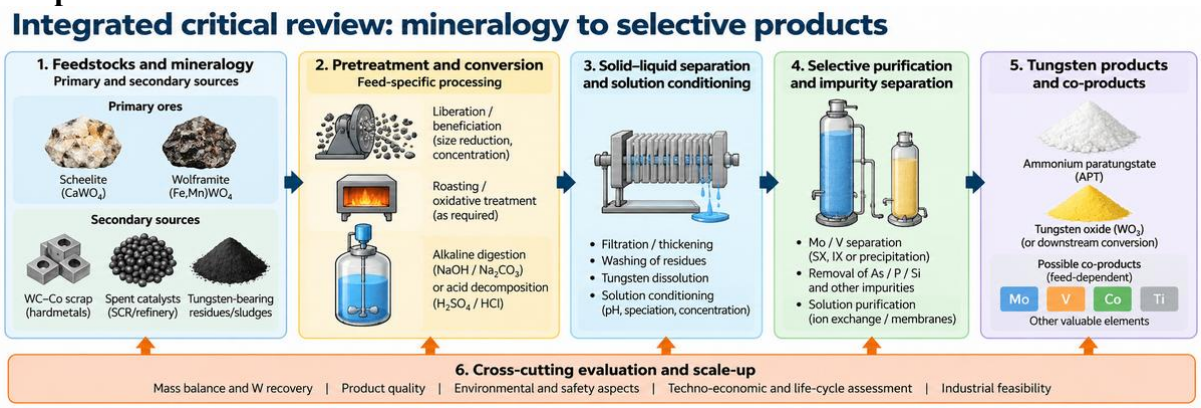
Graphical Abstract



Graphical abstract. Integrated decision pathway from primary and secondary tungsten sources to refined products.
Note. Original conceptual figure created for this review based on the cited literature; arrows represent process logic, not quantified flows.

1. Introduction

Tungsten is strategically significant because of its high melting point, density, wear resistance, and use in cemented carbides and engineered alloys. However, no single universal flowsheet fits all extraction scenarios: scheelite is a calcium tungstate, wolframite is an iron–manganese tungstate solid solution, and tungsten-bearing industrial wastes contain very different mineralogical and chemical matrices. Process selection therefore begins with solid-phase identity and liberation rather than nominal W grade alone (Alguacil & Alonso, 2025; Alguacil et al., 2025; Chen et al., 2025; Han et al., 2021; Shen et al., 2019).

Hydrometallurgical conversion routes commonly deliver soluble tungstate intermediates that can be purified and transformed to ammonium paratungstate (APT). Differences in reagent use, dissolution kinetics, impurity behavior, and product quality determine whether a route is genuinely selective at the flowsheet scale. Figure 1 summarizes the primary-ore decision gates, whereas Figure 2 anticipates the secondary-resource comparison. Table 1 differentiates the major feed families and associated technical barriers (Bai et al., 2026; Baimbetov et al., 2024; Byun et al., 2021; Cao et al., 2021; Chen et al., 2025).

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The critical question of this review is: under what feed-specific chemical and operational conditions can tungsten be recovered at high quality with defensible reagent efficiency, impurity control, and industrial sustainability? This review integrates mineralogical constraints, aqueous chemistry, recovery operations, co-metal separation, APT production, and coupled techno-economic/environmental evaluation. Numerical comparisons are intentionally avoided where the supplied literature list does not establish standardized boundaries.

2. Review Methodology and Evidence Boundaries

The literature base was assembled using 17 topic-specific Boolean search blocks covering tungsten criticality, ore mineralogy, secondary feedstocks, aqueous speciation, alkaline digestion, acid leaching, solid–liquid separation, ammonium paratungstate (APT) production, roasting, direct leaching, Co/Ni removal, W–Mo separation, downstream purification, emerging routes, environmental performance, techno-economic assessment, and integrated flowsheets. The principal search interval was 2020–2026, expanded selectively to 2010–2019 where earlier process evidence was needed. We prioritized journal publications and excluded preprints. The underlying REV7 bibliography contains 138 numbered records; it is a compiled source list, not a fully screened and independently verified systematic-review dataset.

This article is a structured critical review, not a PRISMA systematic review or a meta-analysis. The available source compilation does not establish database-specific search dates, full retrieval and exclusion counts, or independently validated metadata for every record. Accordingly, we do not claim exhaustive retrieval or statistically pooled process performance. Direct experimental evidence on tungsten-bearing feeds is distinguished from analogous studies on other hydrometallurgical systems. Comparisons are restricted where material composition, analytical basis, process boundaries, operating conditions, and downstream losses differ, and any proposed process-selection criterion is treated as an interpretive framework until demonstrated experimentally.

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3. Primary Mineralogy and Secondary Feedstocks

3.1. Scheelite, wolframite, and gangue

Scheelite ($CaWO_4$) and wolframite ($(Fe, Mn)WO_4$) differ in cation chemistry, reactivity, and associated gangue, altering the effectiveness of carbonate, caustic, acidic, and assisted decomposition routes. Mineralogical examination should distinguish liberated tungstate grains from locked intergrowths and should quantify potential penalties from silicates, iron oxides, sulfides, phosphorus, arsenic, and calcium. Resource and ore characterization studies demonstrate why recovery based solely on bulk elemental composition can be misleading (Baimbetov et al., 2024; Bobos et al., 2022; Cheng et al., 2024; Han et al., 2021; Karimova et al., 2025).

Mine wastes and low-grade concentrates add variability in fine-particle behavior, gangue consumption, and secondary phases. Mechanochemical activation and specialized pretreatment may increase apparent accessibility, but liberation benefits should be evaluated alongside grinding energy, reagent carryover, and filtration behavior (Gaur et al., 2025; Li, 2024; Mulenshi et al., 2021; Spooren et al., 2024; Xie et al., 2025).

Figure 1 schematically represents the primary-ore choice. Its arrows emphasize analytical gates rather than a prescribed single flowsheet.

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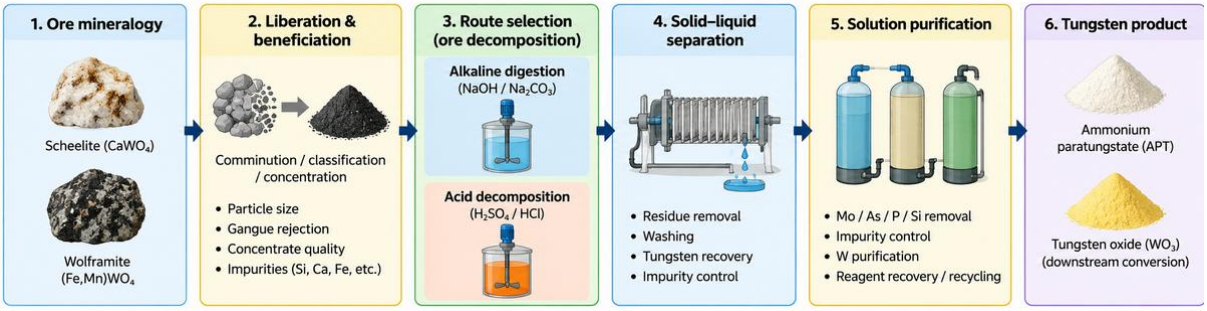

Figure 1. Primary-ore conversion pathway and dominant mineralogical, chemical, and downstream decision gates.
Note. Original conceptual figure created for this review based on the cited literature; arrows represent process logic, not quantified flows.

The comparative framework in Table 1 underscores that high W extraction does not necessarily mean high recovery of saleable W product.

Table 1. Feedstock families and governing hydrometallurgical decisions

Feedstock	Main W host	Principal process concern
Scheelite concentrate	$CaWO_4$	Calcium-rich reaction products; acid/alkaline conversion
Wolframite concentrate	$(Fe, Mn)WO_4$	Fe/Mn deportment; alkaline conversion and solids
WC–Co hardmetal	WC + Co binder	Oxidation, binder removal, Co recovery
Spent SCR catalyst	W oxide on TiO_2 support	W/V/Mo separation; Ti-rich residue
Residues/tailings	Variable W-bearing phases	Low grade, impurity variability, residue stability

Note. Qualitative synthesis; route suitability requires feed-specific experimental verification. No quantitative recovery, TRL, or cost ranking is implied.

3.2. Secondary-resource heterogeneity

Cemented-carbide scrap, grinding sludges, and spent selective catalytic reduction (SCR) catalysts are not interchangeable secondary feeds. Scrap may allow staged binder dissolution, carbide oxidation, or alkaline conversion; catalyst recovery must account for vanadium-bearing phases, titanium-rich supports, sulfur, arsenic, and residual additives. Screening based on a common W assay can therefore select the wrong leach chemistry or

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underestimate solid-residue burdens (Byun et al., 2021; Choi et al., 2018; Ferella, 2020; Kumar et al., 2023).

The clearest sustainability opportunity arises when multiple product streams are considered from the outset. Studies on waste carbides, spent catalysts, and W leach residues indicate opportunities for tungsten together with cobalt, vanadium, titanium, and refractory metals; however, projected co-product credits are not justified unless separations, recovery yields, specifications, and markets are demonstrated (Chen et al., 2023; Huang et al., 2023; Huo et al., 2026; Li et al., 2024; Shemi et al., 2025).

4. Aqueous Chemistry and Reaction Selectivity

4.1. Tungstate and polytungstate behavior

Under sufficiently alkaline conditions, tungsten(VI) is generally represented by tungstate, WO_4^{2-}. Upon acidification, protonation, polymerization, ligand coordination, and solid formation can change the dominant dissolved species and apparent extraction behavior. The relevant chemistry depends on pH, total W concentration, ionic strength, temperature, and the presence of phosphate, peroxide, molybdate, and other coordinating species. Reaction-based studies using phosphate/peroxide chemistry are therefore best interpreted as ligand-specific systems, not generic acid dissolution (Cao et al., 2020; Chen et al., 2020; Gong et al., 2021; Legrand et al., 2025; Wang et al., 2022).

Practically, a leach liquor stable under extraction conditions may become metastable during solvent extraction, dilution, neutralization, or evaporation. A robust speciation model must be tested against measured dissolved W, co-elements, solid residues, and phase identity; a calculated predominance diagram alone does not validate industrial selectivity (Ji et al., 2020; Liu et al., 2021; Wu et al., 2026; Xiao et al., 2023; Xia et al., 2023).

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4.2. Competing metal chemistry

Molybdenum is particularly difficult to reject because molybdate and tungstate have overlapping oxyanion chemistry in many alkaline systems. Vanadium, arsenic, and phosphorus introduce additional extraction or precipitation selectivity challenges. A useful separation protocol consequently reports the distribution of each element across every contact, scrub, strip, precipitation, and recycle stage instead of reporting W extraction in isolation (Cai et al., 2020; Heo et al., 2021; Ismailova et al., 2025; Liu et al., 2025; Liu et al., 2021).

5. Hydrometallurgy of Primary Ores

5.1. Alkaline conversion and kinetic constraints

Alkaline routes include sodium carbonate leaching, caustic conversion, soda fusion, and assisted high-temperature decomposition. Their relative advantages depend on mineralogy, particle size, pressure, reaction time, sodium balance, and gangue chemistry. Studies of wolframite cakes and mixed concentrates demonstrate that claimed conversion efficiency requires attention to sodium reagent consumption and the forms in which Fe, Mn, and silicate impurities leave the system (Bai et al., 2026; Baimbetov et al., 2024; Chen et al., 2022; Li et al., 2022; Zheng et al., 2026).

Pressure leaching, alkali fusion, and intensified physical pretreatment can increase reaction rates, but greater apparent extraction may require higher thermal duty, more equipment, or greater waste-treatment loads. Optimal conditions should be established on a common basis (kg Na_2CO_3 or NaOH per kg W recovered, kWh per kg W product, and net W recovery), not only percentage W dissolution (Johansson et al., 2021; Liu et al., 2023; Luo et al., 2021; Xu & Zhao, 2024; Zhang et al., 2020).

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5.2. Acidic and ligand-assisted scheelite decomposition

Scheelite acid digestion must manage calcium salts, surface alteration, and the possibility of reprecipitating tungsten-containing solids. Hydrochloric, sulfuric, and phosphoric-acid-related routes, often combined with additional ligands or oxidants, differ in the chemistry of released W and in their downstream purification burdens. Phosphate- and peroxide-assisted systems may facilitate dissolution but also alter later solvent extraction and reagent-recycle requirements (Chen et al., 2025; Chen et al., 2020; Gong et al., 2022; Tuncer et al., 2025; Yang et al., 2022).

Reports on resin-enhanced leaching, roasting-assisted decomposition, and sulfuric-acid systems illustrate process intensification strategies. For a meaningful comparison, published extraction performance should be interpreted together with the chemical identity of the W intermediate, impurity carryover, and the reagent treatment needed to reach APT-grade liquor (Gong et al., 2018; Gong et al., 2019; Li et al., 2024; Yang et al., 2022; Yin et al., 2020).

5.3. Solids, filtration, and downstream APT production

Silica-rich gangue and iron-bearing hydrolysis products can produce slurries whose settling or filtration response constrains scale-up. For this reason, solid–liquid separation is part of the recovery chemistry, not an auxiliary operation. Filter-cake washing, suspended-solids entrainment, and liquor hold-up should appear explicitly in the W balance. General hydrometallurgical filtration and coprecipitation analyses are useful analogs but do not substitute for direct tungsten trials (Pereira, 2026a; Pereira, 2026d; Su et al., 2018; Xie et al., 2025).

Production of ammonium paratungstate requires attention to tungstate conditioning, impurity removal, ammonium chemistry, crystallization control, and mother-liquor recycle. Product purity must be specified as independently measured concentrations of critical impurities rather than a nominal crystallization yield. Recent APT-oriented studies point to

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process-specific coupling between dissolution and segmented crystallization (Chen et al., 2026; Pu et al., 2025; Wang et al., 2022; Zhu et al., 2025).

6. Hydrometallurgical Recovery from Secondary Sources

6.1. Oxidative roasting followed by leaching

Roasting can convert refractory carbide or catalyst components into water- or alkali-leachable tungsten species, but it also changes the phase distribution of V, Co, Ti, and other elements. The heating step must be justified against direct leaching through conversion selectivity, exhaust treatment, alkaline consumption, energy demand, and recovery of the solid residue. Studies involving carbonate roasting of WC–Co, SCR catalysts, and mixed spent-catalyst matrices describe materially different reaction networks (Byun et al., 2021; Cao et al., 2021; Liu & Yang, 2021; Wang & Yang, 2021; Wang et al., 2024).

6.2. Direct leaching and selective binder removal

Direct hydrometallurgical routes may reduce the need for thermal treatment but require favorable accessibility and highly selective dissolution. In hardmetals, removing the cobalt binder before carbide conversion can reduce contamination of the W solution; conversely, WC's chemical resistance may require stronger oxidants or a separate conversion step. Recovery evidence must include metal inventory retained in unreacted carbide and cobalt-rich solutions (Huo et al., 2026; Kumar et al., 2023; Shemi et al., 2018; Shemi et al., 2025; Shibata et al., 2014).

Spent-catalyst processing is further complicated by co-dissolution of vanadium, tungsten, and molybdenum. Process optimization should prioritize differential extraction and separation of individual metals over aggregate recovery of valuable metals (Cueva Sola et al., 2022; Cueva Sola et al., 2020; Jeon et al., 2022; Liu et al., 2020; Nie et al., 2022).

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Figure 2 illustrates an integrated recovery sequence for secondary sources; its co-product branch depends on feed composition and is shown downstream.

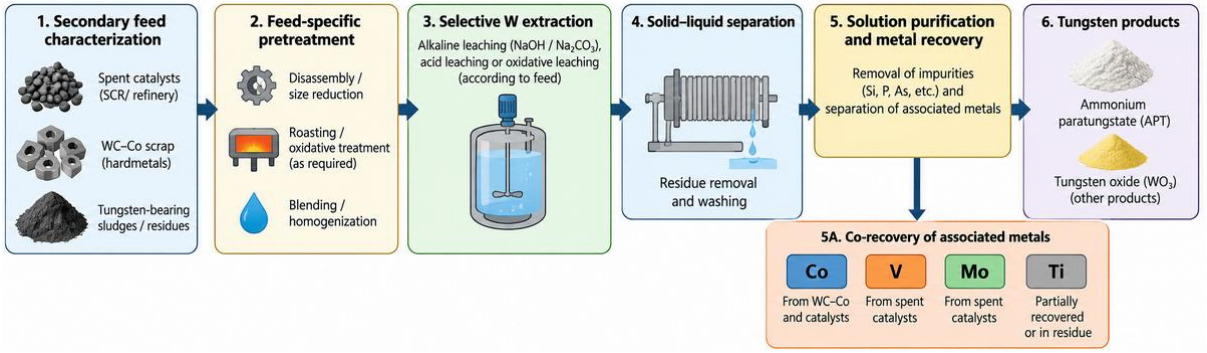

Figure 2**.** Secondary-resource pretreatment, selective leaching, co-metal recovery, and tungsten-product conditioning.
Note. Original conceptual figure created for this review based on the cited literature; arrows represent process logic, not quantified flows.

For SCR catalysts, multi-metal extraction options include alkaline leaching, carbonate conversion, acid-assisted approaches, and staged sorption. Compare these options within the same environmental boundaries, accounting for titanium-rich residue and washing streams (Cueva Sola et al., 2024; Moon et al., 2019; Qian et al., 2022; Su et al., 2020; Wu et al., 2025).

6.3. Co/Ni, vanadium, and molybdenum partitioning

W-bearing secondary materials can contain a significant fraction of recoverable metals not present in primary tungstate ores. For spent catalysts, track vanadium through individual leach, adsorption, and purification steps; for cemented carbides, evaluate cobalt or nickel binder removal for both recovery yield and W loss. Multiple studies highlight differential adsorption and sequential recovery as practical alternatives to indiscriminate dissolution (Heo et al., 2021; Hong et al., 2023; Liu et al., 2023; Sknar et al., 2024; Xiao et al., 2022).

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7. Purification, W–Mo Separation, and Final Products

7.1. Solvent extraction, ion exchange, and adsorption

Screen solvent extraction (SX), ion exchange (IX), adsorption, and selective precipitation using actual feed-liquor matrices. W distribution depends on pH, ligands, competing ions, extractant speciation, and organic-phase loading. One equilibrium distribution ratio alone cannot judge the process: multi-stage selectivity, stripping efficiency, entrainment, and solvent loss determine industrial relevance (Chen et al., 2021; Chen et al., 2020; Igosawa et al., 2022; Kang et al., 2025; Lozano-Blanco & Alguacil, 2026).

In W–Mo systems, different separation concepts exploit differential coordination chemistry, pH-sensitive extraction, and precipitation chemistry. These studies should be assessed for achievable Mo impurity concentration in the final W product, reagent demand, recycling feasibility, and how separation changes across variable W: Mo ratios (Cai et al., 2020; Ismailova et al., 2025; Wen et al., 2025; Wu et al., 2026; Zhu et al., 2024).

As shown in Figure 3, separation depends on the full liquor chemistry. Ion exchange and chelating-resin design principles from broader hydrometallurgy provide supporting operational guidance but should be labeled as analogical when W-selectivity data are absent (Dauletbakova et al., 2025; Hong et al., 2023; Pereira, 2026b; Yuan et al., 2024; Zeng et al., 2024).

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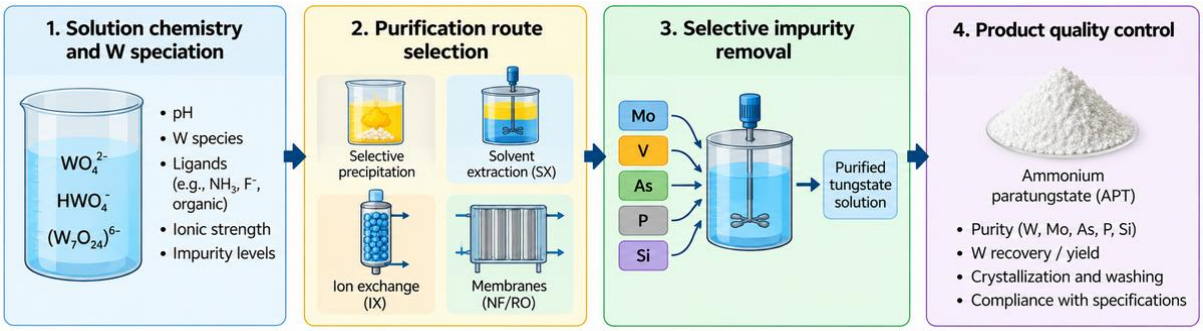

Figure 3. Solution-speciation and separation decision framework for impurity control and tungsten-product quality.
Note. Original conceptual figure created for this review based on the cited literature; arrows represent process logic, not quantified flows.

7.2. Membranes, precipitation, and APT quality

Membrane-based technologies and electrodialysis can help recover salts or influence ionic separations; their industrial value in W circuits still depends on membrane selectivity, fouling, counter-ion transport, and stability in real liquor. Generic heavy-metal electrodialysis results are a methodological analogy and cannot establish tungsten recoveries without W-specific testing (Alkhadra & Bazant, 2022; Dauletbakova et al., 2025; Lin et al., 2025; Wu et al., 2016).

Precipitation and crystallization are not merely final concentration operations: calcium, molybdenum, arsenic, phosphorus, and residual sodium can affect purity, crystal habit, and recoverable W in mother liquors. Process requirements should link the chosen W intermediate to target product specifications and a complete recycle/bleed strategy (Chen et al., 2026; Ji et al., 2020; Pu et al., 2025; Zhu et al., 2025).

Table 2 summarizes qualitative technological trade-offs without inventing performance rankings. Every option is conditional on speciation and feed impurity levels.

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Table 2. Comparative selection logic for tungsten-liquor purification

Unit operation	Potential advantage	Primary constraint
Solvent extraction	Stage-wise selectivity and strip/recycle options	Extractant losses, emulsions, ligand effects
Ion exchange/adsorption	Useful for dilute solutions and polishing	Capacity, competing ions, regeneration waste
Selective precipitation	Simple solids route for targeted chemistry	Co-precipitation, washing, impurity occlusion
Membranes/electrodialysis	Salt management and selective transport potential	Fouling, energy demand, real-liquor validation
APT crystallization	Marketable intermediate production	Mother-liquor loops and impurity inclusions

Note. Qualitative synthesis; route suitability requires feed-specific experimental verification. No quantitative recovery, TRL, or cost ranking is implied.

8. Emerging Intensification and Circular Processing

Mechanochemical activation, microwave-assisted alkaline fusion, acoustic or hydrodynamic cavitation, novel ionic liquids, and solvometallurgical extraction offer routes to change reaction rates or downstream selectivity. The key challenge is to distinguish a true decrease in total process burden from displacement of reagent demand into pretreatment, solvent synthesis, regeneration, or post-treatment (Igosawa et al., 2022; Johansson et al., 2021; Mulenshi et al., 2021; Orefice et al., 2022; Spooren et al., 2024).

The use of hydrogen peroxide, complexing ligands, and process-specific multi-stage extraction also illustrates a broader point: improvements in leaching kinetics may worsen purification unless ligand decomposition, W species stability, and impurity pathways are quantified (Jia et al., 2026; Ji et al., 2020; Liu et al., 2021; Wu et al., 2026; Yin et al., 2020).

General deep eutectic solvent knowledge provides a basis for solvent-screening hypotheses, but it does not establish W-specific extraction efficiency or industrial maturity. A defensible development program should report solvent stability, reproducibility, phase disengagement, extraction–stripping cycles, loss factors, corrosion, and environmental burdens (Pereira, 2026c; Orefice et al., 2022; Qing et al., 2026).

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9. Environmental Performance and Resource Circularity

A credible environmental comparison of primary and secondary tungsten should share a common functional unit and account for upstream beneficiation or scrap collection, reagent production, thermal conversion, leaching, purification, product finishing, wastewater treatment, and residues. It is not adequate to claim that recycling always has lower energy or CO_2 impacts without accounting for feed collection, scrap grade, process chemistry, and co-product allocation (Ferella, 2020; Han et al., 2021; Kumar et al., 2023; Zeiler et al., 2021; Zhu et al., 2024).

Industrial W circuits can generate arsenic-bearing sludges, high-salt alkaline liquors, spent organics, and metal-bearing residues. Treatment must consider leachability, long-term stability, and the potential for secondary metal recovery. Waste tungsten leach-residue studies show that upstream metal-recovery choices affect whether downstream residues can be safely valorized (Cao et al., 2024; Chen et al., 2023; Chen et al., 2021; Wu et al., 2023; Zheng et al., 2024).

Integrated sustainability indicators should therefore include kg reagent per kg W product, specific heat and electricity use, % W and impurity closure, dissolved losses to purge, effluent salinity, solid residue mass and hazard, and product purity. Where original studies do not report comparable boundaries, quantitative ranking should be withheld rather than inferred (Dimitrijević et al., 2024; Huang et al., 2023; Li et al., 2024; Wu et al., 2025; Wu et al., 2020).

10. Techno-Economic Assessment and Scale-Up

A tungsten hydrometallurgical techno-economic analysis must begin with feed variability, pre-concentration, W grade and liberation, reaction duty, process residence time, reagent recovery, dewatering and residue storage, and specification-dependent revenue. APT pricing and cobalt/vanadium co-product credits should enter scenario analysis only after

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establishing consistent yield, purity, and market assumptions (Alguacil & Alonso, 2025; Chen et al., 2025; Han et al., 2021; Kumar et al., 2023; Shen et al., 2019).

Useful screening indicators are overall W recovery to qualified product; reagent consumption net of regeneration; kWh per tonne of saleable W contained; extraction and stripping stage count; solids handling intensity; and residue management expenditure. The uncertainties most likely to dominate early feasibility are feed heterogeneity, co-dissolution of penalty elements, uncertain recycle accumulation, and the gap between laboratory batch extraction and continuous process operation (Chen et al., 2022; Gaur et al., 2025; Li et al., 2024; Lozano-Blanco & Alguacil, 2026; Zeiler et al., 2021).

Figure 4 describes an evidence hierarchy from exploratory chemistry to industrial design. Publication of a batch experiment does not, by itself, justify a numerical technology readiness level (TRL).

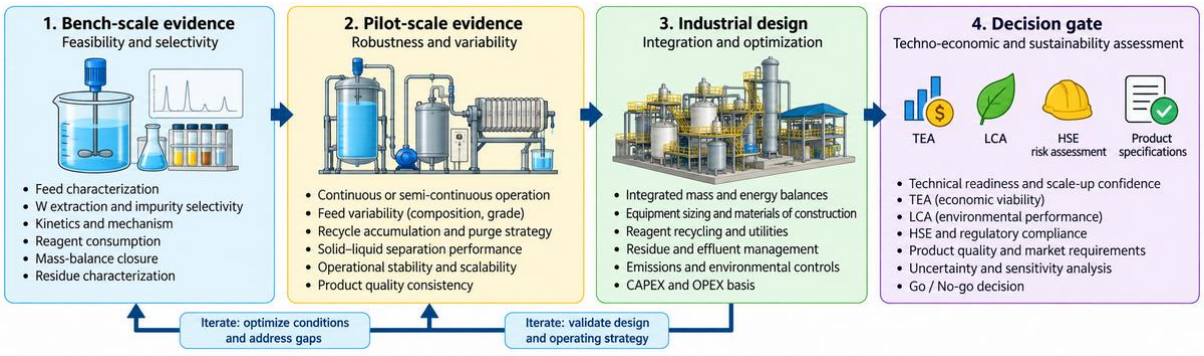

Figure 4. Minimum evidence progression linking laboratory selectivity to pilot testing and integrated industrial decisions.
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Table 3 presents a decision matrix suitable for assessing alternative W feedstocks without assigning unsupported recovery, cost, or environmental values.

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Table 3. Proposed process screening matrix and data requirements

Criterion	Required evidence	Comparability condition
Extraction	W in feed, liquor, residue, and wash	Same elemental and moisture basis
Product quality	Measured APT/tungstate impurities	Common product specification
Reagents	Fresh input, regeneration, and purge	Net kg reagent/kg saleable W
Energy	Roast, heat, pressure, drying, electricity	kWh or MJ/kg saleable W
Co-products	Recovered metal grades and realized yields	Net saleable revenue, no assumed credits
Environment	Residues, effluent, emissions, toxicity	Common system boundary and allocation

Note. Qualitative synthesis; route suitability requires feed-specific experimental verification. No quantitative recovery, TRL, or cost ranking is implied.

11. Critical Synthesis and Research Priorities

The principal technical barrier is not dissolution alone. Tungsten must be converted from mineralogically variable feeds into stable, impurity-controlled liquors and ultimately saleable products, while elemental, water, energy, and reagent balances are closed. Scheelite and wolframite differ fundamentally in their calcium versus iron–manganese tungstate hosts; secondary sources are instead governed by binder chemistry, catalyst supports, oxidation state, and their co-metal inventory. These distinctions limit the transferability of extraction percentages reported under unlike test conditions. The decisive comparison is therefore overall product recovery and purity at a defined process boundary, not isolated W dissolution.

Three experimental gaps warrant immediate attention. First, validate coupled speciation and kinetic models using measured phase changes and solutions representative of industrial ionic strengths and impurity levels. Second, W–Mo and W–V separation requires multi-cycle solvent extraction, ion exchange, or precipitation trials with documented stripping, recycle, and impurity build-up. Third, scale-up evidence must encompass settling, filtration, washing, silica-rich residues, and crystallization slurries. Without these measurements, promising bench-

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scale selectivity may be offset by solution losses or difficult solids handling (Gong et al., 2022; Liu et al., 2023; Wang et al., 2024).

Two further priorities connect process chemistry to industrial feasibility: demonstrable recovery or regeneration of alkaline and acidic reagents, and integrated techno-economic and environmental assessments based on functionally equivalent saleable products. The necessary inventory includes Na, Ca, S, P, Cl, W, co-metals, water, and thermal inputs across every recycle and purge. Hybrid pyrometallurgical–hydrometallurgical routes must also account for off-gas capture, residue treatment, and reagent regeneration before inferring their comparative benefits (Boury et al., 2023; Chen et al., 2021; Li et al., 2020; Ren et al., 2020).

A staged qualification framework follows from these constraints: (i) establish mineralogical deportment and impurity variability; (ii) measure selective dissolution and complete downstream purification on representative process liquor; and (iii) demonstrate recycle stability, product compliance, and reconciled mass and energy balances before applying risk-adjusted techno-economic assessment (TEA) and life-cycle assessment (LCA). The framework separates chemical feasibility from industrial readiness without assigning unsupported technology-readiness levels (Jin et al., 2023; Liu et al., 2023; Shen et al., 2019; Wang et al., 2026; Zeng et al., 2026).

12. Conclusions

Hydrometallurgical tungsten recovery is best understood as a feed-dependent sequence of mineral decomposition, aqueous speciation control, selective purification, and product formation rather than an isolated leaching operation. Scheelite, wolframite, WC–Co scrap, spent catalysts, and tungsten residues require different reaction strategies and impurity-management approaches. W–Mo separation and qualified APT production remain key downstream decision points. Intensification concepts are promising, but their value depends on demonstrated reagent recycling, material balances, scalable solids handling, and stable product

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quality. The proposed evidence-gated evaluation framework connects laboratory chemistry to engineering design and highlights where additional pilot validation, environmentally comprehensive balances, and comparable economic data are needed.

Declarations

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Conflict of Interest

The author declares no conflict of interest.

Data Availability

No new experimental datasets were generated. All quantitative values discussed in the review are traceable to the cited literature.

Author Contributions

The author performed conceptualization, critical analysis, literature synthesis, visualization, and manuscript preparation

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