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# Techno-Economic Performance and Circularity Metrics of Zirconium Processing Technologies: From Zircon Decomposition to Nuclear-Grade Zirconium

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## Abstract

Researchers commonly compare zirconium processing routes by extraction yield, separation factor, or individual unit-operation efficiency, even though their economic and environmental significance depends on the final product and the entire sequence of transformation, purification, recycling, and waste management. This critical review develops a harmonized comparison framework for alkaline, chloride, hydrometallurgical, hybrid, electrochemical, and secondary-resource routes from zircon decomposition toward high-purity zirconium intermediates and nuclear-grade products. A structured, non-systematic evidence synthesis of the supplied 2010–2026 bibliography examines system boundaries, closed mass balances, Zr/Hf rejection, reagent and water intensity, energy and carbon accounting, residue burdens, cost architecture, evidence maturity, and uncertainty. The analysis shows why single-stage recovery and laboratory separation factors do not establish flowsheet competitiveness: impurity specifications, scrub and strip losses, recycle performance, salt generation, and scale-dependent utilities determine overall outcomes. We propose an explicit hierarchy of comparable functional units, measured versus modeled metrics, and evidence-gated multicriteria screening. The framework identifies reporting priorities required for credible techno-economic and life-cycle comparisons without extrapolating unverified commercial performance from laboratory data.

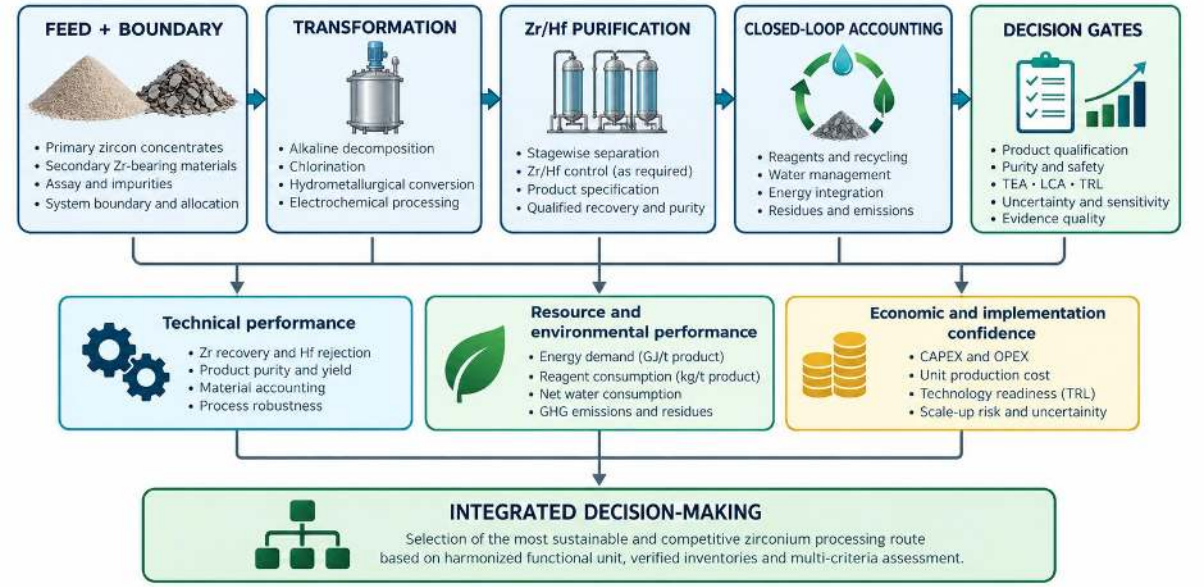
**Keywords:** zirconium; zircon decomposition; zirconium–hafnium separation; techno-economic assessment; life-cycle assessment; reagent circularity

## Highlights

- Common product boundaries are prerequisites for defensible zirconium route comparisons.
- Full-stage yield and Hf rejection must be assessed jointly with reagent recycle.
- Laboratory selectivity cannot substitute for continuous industrial mass and energy balances.
- An evidence-gated TEA–LCA–TRL matrix guides zirconium process development.

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## Graphical Abstract




**Graphical Abstract.** Unified feed-to-product comparison logic.
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## 1. Introduction: Why Recovery Is Not Enough

Zircon ($ZrSiO_4$) provides a refractory mineral starting point for zirconium chemicals, ceramics, alloys, and nuclear applications, but these end uses impose different purity requirements and process boundaries. Lubbe and Crouse's (2023) review of zircon feedstocks and Xu et al.'s (2015) overview of nuclear-grade production describe markedly different downstream requirements. Consequently, high mineral decomposition, zirconium extraction, or intermediate oxide yield alone cannot rank complete technologies.

The distinctive industrial difficulty is the chemical similarity of Zr(IV) and Hf(IV). Banda and Lee (2015), Wang and Lee (2016), and Dong et al. (2025) show that separation depends strongly on coordination, acidity, complexing species, and extraction chemistry. Even strong laboratory selectivity cannot be taken as a substitute for attainable product purity after repeated contacts and reagent recycling. This review therefore compares product-qualified yield rather than isolated extraction.

The research question is: which minimum set of transparent physical, environmental, economic, and evidence-quality indicators permits a reproducible comparison of complete

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zirconium processing routes at an equivalent qualified-product boundary? Figure 1 maps those boundaries, and Table 1 specifies the functional units. Unlike the author's previous review, "Recovery of Zirconium from Primary and Secondary Resources: Chemistry, Zr/Hf Separation, Electrochemical Routes, and Industrial Perspectives," which surveyed recovery chemistry and route options, this article develops a harmonized qualified-product TEA–LCA–circularity framework integrating independent Zr and Hf balances, evidence gates, uncertainty, and multicriteria decision analysis. Its contribution is not a claim of originality for Zr/Hf extraction chemistry, already reviewed in detail by Dong et al. (2025) and Rodrigues et al. (2026), but a comparative decision methodology across full process chains. This manuscript presents a newly organized evaluative framework and schematic syntheses; it cites overlapping literature where relevant, rather than presenting it as newly generated experimental evidence.

**Review approach and evidence limitations.**

This critical narrative review evaluates 141 bibliography entries assembled for the manuscript and categorized through thirteen topic-specific search themes (full reproducible strings in Supplementary Table S1). Of these records, 100/141 (70.9%) are dated 2020–2026, and 107/141 (75.9%) are dated 2019–2026. The working compilation comprised a pre-existing 111-record core plus 30 additional records; this historical distinction refers to compilation order, not to separate evidence grades. On 6 November 2026, the supplied reference list and manuscript were reconciled editorially for this revision; this date does not reflect a fresh execution of every database query. Title, date, DOI metadata, relevance, and full-text validation must be distinguished: inclusion in the list does not establish that all publisher full texts or numerical claims have been independently checked. Source-specific numerical process performance is therefore not pooled across incompatible feeds, media, purification specifications, and scales. This is a structured critical narrative review, not a PRISMA systematic review.

**Literature-search strategy: thirteen thematic Boolean expressions**

S01. ("zircon" OR "zirconium silicate") AND ("alkali fusion" OR "alkaline decomposition")

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S02. ("zircon" OR "zirconium") AND ("chlorination" OR "chloride route" OR "zirconium tetrachloride")

S03. ("zirconium" AND "hafnium") AND ("solvent extraction" OR "separation factor")

S04. ("zirconium" AND "hafnium") AND ("TBP" OR "tributyl phosphate" OR "MIBK")

S05. ("zirconium" AND "hafnium") AND ("D2EHPA" OR "PC88A" OR "Cyanex" OR "organophosphorus")

S06. ("zirconium" AND "hafnium") AND ("ion exchange" OR "chromatography" OR "resin")

S07. ("zirconium" AND "hafnium") AND ("ionic liquid" OR "membrane" OR "MOF" OR "novel ligand")

S08. ("nuclear grade zirconium" OR "zirconium sponge") AND ("purity" OR "hafnium removal")

S09. ("zirconium" OR "zircon") AND ("mass balance" OR "recovery" OR "process simulation")

S10. ("zirconium processing" OR "zircon decomposition") AND ("energy" OR "carbon" OR "plasma")

S11. ("zirconium" OR "zircon") AND ("reagent recycle" OR "water consumption" OR "circularity")

S12. ("zirconium" OR "zircon") AND ("techno-economic" OR "CAPEX" OR "OPEX" OR "life cycle assessment")

S13. ("zirconium recycling" OR "zircaloy recycling") AND ("technology readiness" OR "uncertainty" OR "multicriteria")

Search implementation note. Strings document reproducible thematic queries for a subsequent database rerun; database coverage, per-query retrieval counts, deduplication, last executed search date, and source-level full-text checks were not retained in the supplied materials. Do not interpret these terms as a verified contemporaneous search log.

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## 2. System Boundaries for Comparing Zirconium Technologies

An explicit functional unit must state product chemistry, Zr purity, Hf ceiling, and physical form. A tonne of zircon concentrate, a tonne of commercial $ZrO_2$, and a tonne of nuclear-grade zirconium metal are not interchangeable denominators. Gediga et al. (2019) address upstream zircon sand life-cycle burdens; this upstream inventory alone cannot represent nuclear-grade metal production. Similarly, recovery of Hf-bearing intermediates cannot be assessed with the same purity gate as Hf-depleted nuclear zirconium.

Gate-to-gate results are useful for experiments but omit upstream caustic, chloride, electricity, and solvent supply, as well as downstream neutralization and product finishing. Cradle-to-gate boundaries should separately account for mining, concentration, conversion, Zr/Hf purification, chemical recovery, product finishing, and waste treatment. The secondary-feed burden must be allocated transparently: a zero-burden scrap assumption may be appropriate for a particular cutoff model but is not an empirical property of scrap itself (Liu et al., 2026; Vestal et al., 2023).

Figure 1 shows a primary product path; recycling connects at the relevant conversion or purification step and is never treated as an equivalent incoming mineral without reporting its composition. A comparative study must publish allocation rules for co-products, especially hafnium, silica, and recovered acids. The distinction between gross loop circulation and net purchased inputs is critical to the flowsheet interpretation.

Table 1 summarizes the three product-level functional units required for comparable economic and environmental assessments.

**Table 1.** Reference product boundaries for zirconium-system comparisons

| Boundary | Functional unit | Mandatory qualifier |
|---|---|---|
| **Primary conversion** | 1 t purified Zr intermediate | Chemical form; Zr/Hf assay |
| **Chloride production** | 1 t qualified $ZrCl_4$ | Moisture; Hf and trace-metal thresholds |
| **Metal production** | 1 t qualified Zr metal | Grade; sponge/ingot; downstream finishing |

*Note.* This review proposes illustrative boundary definitions; numerical purity standards must follow the intended product specification. These are separate functional units; a route meeting an intermediate-grade specification cannot automatically be credited with nuclear-grade product performance.

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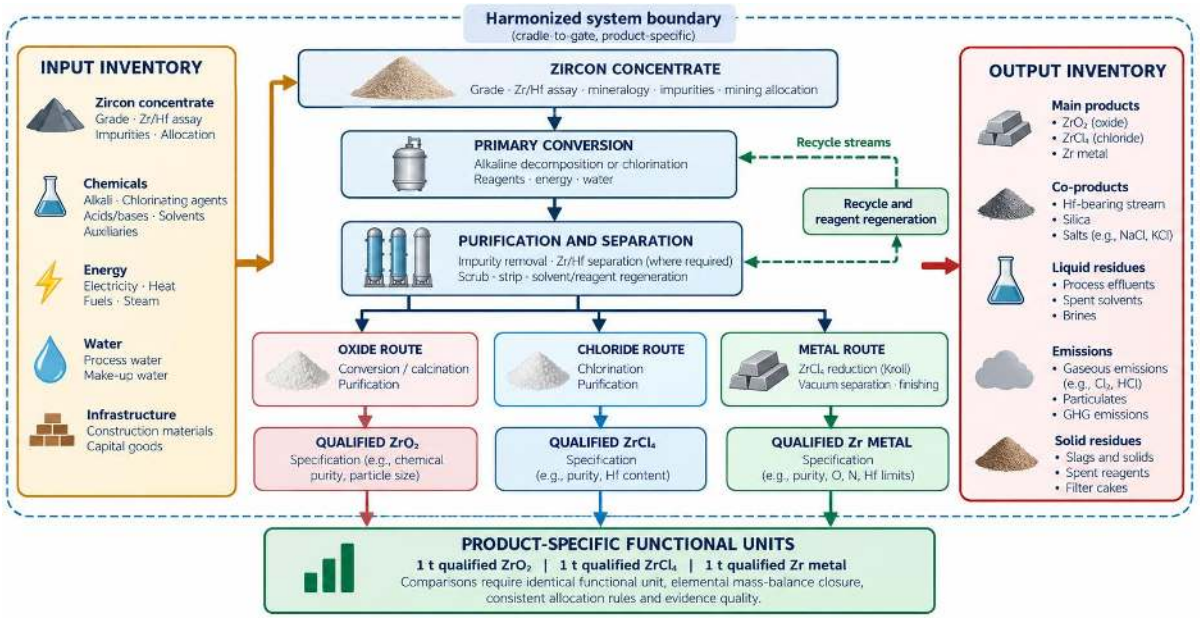



**Figure 1.** Harmonized primary-process boundary from concentrate to qualified zirconium product.
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**Evidence-based comparison: Boundary-setting and mineral-feed comparability**

The available evidence spans feedstock selection, product specifications, and process inventories, but a consistent comparison requires matching chemical grade and functional unit. The zircon feedstock overview of Lubbe et al. (2023) is relevant to this boundary problem; it does not, by itself, validate a single route as optimal across ceramic and nuclear products.

For zircon-derived chemicals, compositional variability, competing end uses, and quality requirements should be separated from process efficiency. Lubbe et al. (2023) therefore use the feedstock perspective to define the range of inputs rather than assign commercial performance.

**3. Reference Zirconium Processing Flowsheets**

In alkaline conversion, zircon reacts with alkali to open a chemically resistant silicate structure before water washing, acid conversion, and zirconium oxychloride production. Studies by Liu et al. (2016), Song et al. (2020), Sun et al. (2024), and Singh et al. (2021) focus on phase formation, decomposition, and intermediate purity. Their findings show that feed mineralogy, alkali ratio, and washing sequence can alter silica separation and soluble-

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salt generation, but no single validated industrial flowsheet combines the reported laboratory conditions.

Chloride-based processing offers a different purification logic, frequently involving volatile chloride intermediates and gas-handling demands. The critical comparison is not solely reaction temperature but the complete chlorine balance, off-gas treatment, impurity co-volatilization, equipment corrosion, and recycle efficiency. Nuclear-grade chloride specifications impose more stringent process integration than general-purpose zirconia production (Xu et al., 2015; Lubbe & Crouse, 2023).

Hydrometallurgical routes employ precipitation, solvent extraction, ion exchange, and tailored complexing media. Amaral and Morais (2020), He et al. (2021), Ismail et al. (2025), and Rozana et al. (2025) represent different acid and extractant systems and cannot be ranked by a single extraction-factor table. Plasma treatment (Yugeswaran et al., 2015; Yelatontsev et al., 2026), molten-salt electrochemistry (Li et al., 2021; Massot et al., 2024), and recycling of Zircaloy (Vestal et al., 2023; Davis & Zhang, 2024) may change the conventional mineral-to-metal sequence but require explicit feed-conditioning and finishing assumptions. Figure 2 depicts the route classes and their interface points.

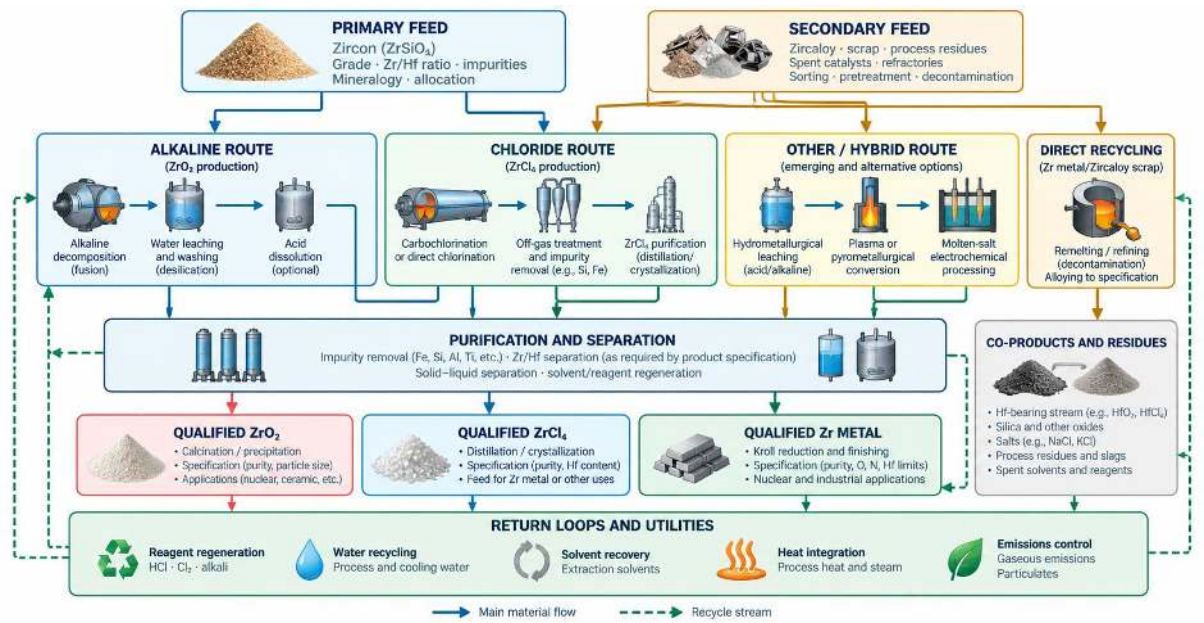



**Figure 2.** Conceptual comparison of primary and secondary zirconium route families.
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**Evidence-based comparison: Feed conversion and reference processing pathways**

Conversion studies address distinct transformations and product targets. The comparison below differentiates decomposition and intermediate preparation from specialty finishing and secondary-feed treatment; none of these topics alone constitutes an integrated plant-level inventory.

Solution purification and specialized alloy treatment illustrate different system boundaries. Ali (2022) considers a phosphate-based extractant for zirconium oxide purification, whereas Chandramohan et al. (2026) focus on alkali-fusion surface decontamination, and Cheje Machaca et al. (2026) focus on recovery from tin slags. These cannot be compared on extraction yield without accounting for the feed assays and saleable products.

Feed mineralogy and final-grade separation frame the problem from opposite ends: Franco-Magalhães et al. (2021) address zirconium mineral occurrence, Ismail et al. (2025) address anion-exchange removal of hafnium from leach solutions, and Jia et al. (2024) address Zr–Hf alloy diffusion and properties. The alloy study is downstream context, not direct evidence of extraction performance.

Liu et al. (2014, 2016) address washing and phase behavior during alkali conversion, while Ma et al. (2026) discuss zirconium occurrence in complex beneficiation products. Their relevance lies in the sensitivity of material routing to intermediate phases and feed composition, not universal conversion efficiency.

Molten-salt processing and specialty alloys introduce further constraints. Mirza et al. (2023) review nuclear electrochemical applications; Mukhachev et al. (2024) address zirconium–boron alloy refining; Nurhadini et al. (2025) focus on zirconium oxychloride preparation. These routes involve different purification endpoints and cannot share one unqualified denominator.

The solvent system and acid matrix are central to Zr/Hf separation. Rozana et al. (2024, 2025) examine tributyl phosphate systems with different diluents and feed solutions,

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whereas Samin et al. (2024) focus on oxide preparation. The former require stagewise purification data; the latter requires explicit oxide-product criteria.

Samin et al. (2022) examine low-TENORM zirconia, Singh et al. (2021) report a high-purity oxychloride pathway for ceramics, and Song et al. (2020) examine alkali fusion followed by water leaching. Radioactivity control, ceramic purity, and intermediate conversion are separate outcome dimensions.

Subuki et al. (2020) address caustic fusion, Supriadi et al. (2025) focus on kinetics and TENORM in oxychloride manufacture, and Tang et al. (2023) investigate ion-imprinted membranes for hafnium enrichment. Connecting these operations into a complete route would require balances for recovery, contaminant deportment, and regeneration.

Trisnawati et al. (2022) consider phosphate separation from zircon tailings, Velasquez et al. (2026) investigate zircon behavior in glass melting, and Widayat et al. (2024) concern catalytic zirconia. Their different objectives help identify alternative products and residues but do not justify direct cross-route cost rankings.

Xu et al. (2015) provide nuclear-grade production context, whereas Yelatontsev et al. (2026) and Yugeswaran et al. (2015) address plasma-based mineral processing. Any asserted environmental advantage of plasma treatment should be tested against measured electricity intensity, silica removal, gas treatment, and downstream product quality.

In-flight silica removal during plasma dissociation (Yugeswaran et al., 2015) may change downstream separation needs; the net benefit remains conditional on recovering volatile or entrained materials and on the full energy balance.

**4. Mass-Balance Metrics**

The governing condition is element-by-element closure over a fixed reporting period. For zirconium, feed Zr must be reconciled against qualified product, residues, aqueous losses, purge streams, and inventory variation; hafnium requires an independent balance. Total zirconium recovery is not equal to qualified nuclear-grade yield when an additional separation step removes Zr with the Hf-rich fraction. Liu et al. (2014), Song et al. (2020), and Sun et al. (2024) illustrate relevant primary-process mass-transfer questions.

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On an element-mass basis, qualified zirconium yield is Y_Zr = m(Zr in qualified product)/m(Zr in feed); hafnium rejection is R_Hf = 1 − m(Hf in qualified product)/m(Hf in feed); and the hafnium decontamination factor is DF_Hf = (m_Hf/m_Zr)_feed / (m_Hf/m_Zr)_qualified product. The paired values Y_Zr, R_Hf, and DF_Hf describe the trade-off between selectivity and zirconium loss; none alone certifies a nuclear-grade product. Report I_R = m(fresh reagent)/m(qualified Zr product) and I_W = m(net makeup water)/m(qualified Zr product), specifying whether product mass denotes contained Zr or gross material. All indicators require a consistent time interval, allocation method, independent Zr/Hf closure residuals, and a stated inventory-change convention.

In secondary routes, pretreatment and cladding contamination introduce distinct metal-bearing and nonmetallic losses. Vestal et al. (2023) and Hur et al. (2021) provide relevant process contexts, but without consistent inventories, their recovery metrics should not be merged numerically with primary-concentrate results.

Table 2 provides reproducible metric definitions and flags denominator ambiguity.

**Table 2.** Harmonized material and separation metrics

| Metric | Definition | Reporting requirement |
|---|---|---|
| **Hf decontamination factor (DF_Hf)** | (Hf/Zr)_feed / (Hf/Zr)_qualified product | Element-mass basis; detection limits; final Hf/Zr |
| **Qualified Zr yield** | Zr in saleable product / feed Zr | Feed assay, inventory change |
| **Hf rejection** | 1 − Hf in product/feed Hf | Full Hf deportment |
| **Separation factor** | D_Zr / D_Hf | Phase, acidity, temperature |
| **Net water intensity** | Fresh water / qualified Zr product | Purge, evaporation, recycling |
| **Reagent intensity** | Fresh reagent / qualified Zr product | Net vs gross circulation |

*Note.* All ratios dimensionless except mass-intensity indicators (t/t); definitions are original review recommendations.

## Evidence-based comparison: Mass-yield reporting and feed-to-product accounting

Evidence from effluent treatment and mineral recovery lies outside a unified zircon-to-metal process balance. Such sources can inform recovery definitions only where streams are measured at comparable boundaries.

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Eliwa (2024) considers zirconium and yttrium capture from effluents, whereas Rao et al. (2024) examine rare-earth-bearing placer minerals. Neither topic should be substituted for a qualified zirconium-product yield without feed-to-product reconciliation.

**5. Separation-Performance Metrics**

The equilibrium separation factor $\alpha_{Zr/Hf} = D_{Zr}/D_{Hf}$ measures a defined distribution equilibrium, not plant separation performance. It requires aqueous and organic composition, contact time, loading, temperature, acidity, and extraction direction; $\alpha_{Zr/Hf} < 1$ may be favorable where Hf rather than Zr is preferentially extracted. Three noninterchangeable levels should be reported: (i) equilibrium selectivity under controlled conditions; (ii) multistage extraction–scrubbing–stripping performance including reagent degradation and metal losses; and (iii) qualified final-product performance based on $Y_{Zr}$, $R_{Hf}$, $DF_{Hf}$ and the contractual Hf/Zr ceiling (Banda et al., 2012, 2013; Amaral & Morais, 2020; Dong et al., 2025).

Laboratory comparisons should report phase ratio, stage count, scrub-related zirconium loss, stripping completeness, organic carryover, and final Hf/Zr. The system of Ma et al. (2021) and tailored extractants of Wang et al. (2023), Chen et al. (2026), and Xie et al. (2026) show development toward selectivity, while resins studied by Felipe and Ladeira (2018), Hu et al. (2025), and Wang et al. (2025) suggest different regeneration and breakthrough constraints. These represent different process architectures rather than directly interchangeable extractants.

Figure 3 places the final product purity after scrubbing and stripping and treats reagent losses as integral to the separation assessment. Multiple laboratory extractions from synthetic solutions should not be ranked as equivalent to continuous loaded-liquor processing without feed-impurity characterization and stability data.

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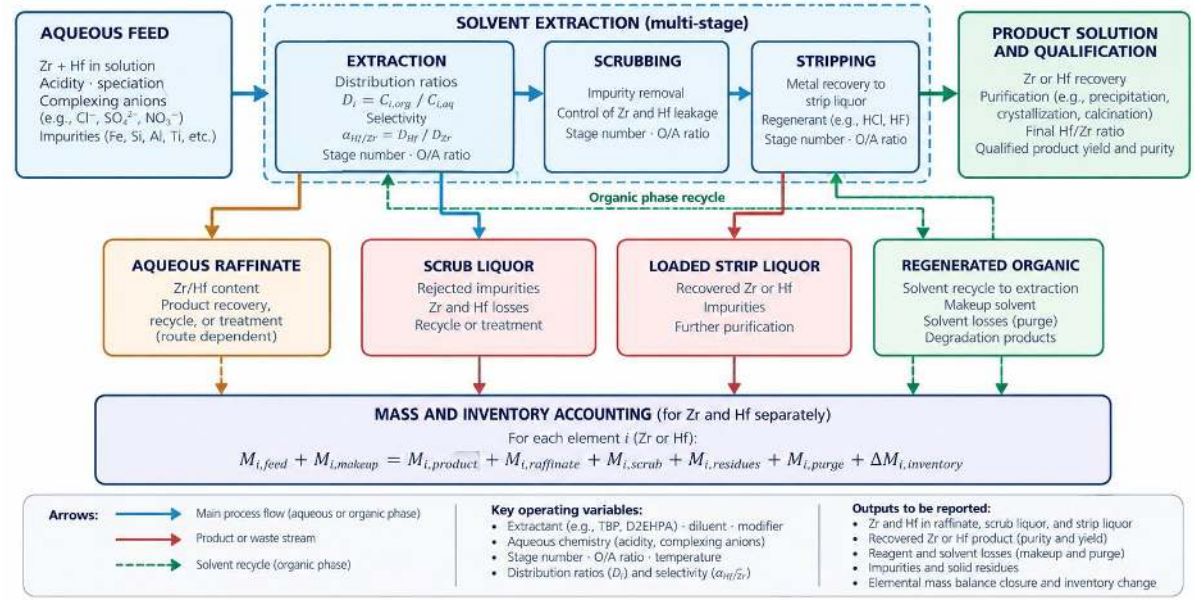



**Figure 3.** Stagewise Zr/Hf separation and material-loss accounting.
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**Evidence-based comparison: Speciation, separation, and final purity**

Zr/Hf separation studies fall into the following mechanistic and process families. This classification prioritizes feed speciation, the preferred extracted element, continuous operability, recycle losses, and product qualification rather than the number of reported laboratory extraction tests. No cross-family ranking is possible from equilibrium separation factors alone.

A. Benchmark TBP and conventional solvent systems. Tributyl phosphate (TBP) in nitrate media provides an established comparative benchmark for zirconium extraction and nuclear-oriented oxide purification (Amaral & Morais, 2020; Amaral et al., 2020; Ravi Kanth et al., 2020). TBP-modified particles and mixed-extractant studies (Aliakbari et al., 2014; Taghizadeh et al., 2011; Yadollahi et al., 2018) explore alternative phase contacts and synergism, but comparisons must distinguish batch partitioning from countercurrent flowsheets. Acid consumption, extractant solubility, entrainment, stripping completeness, and loss of Zr in Hf-rich streams determine achievable product yield. The benchmark value of conventional systems is process familiarity, not universal selectivity.

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B. Zirconium-selective extraction systems. Zr-selective strategies include amine-based chloride systems (Banda et al., 2012, 2013a, 2013b), high-acidity trioctylamine extraction (Tian et al., 2025), amic-acid extractants (Ma et al., 2021), and mixed organophosphorus systems (Wang et al., 2013, 2015). Their chemical advantages depend on the changing population of chloride, sulfate, or other metal complexes; a nominally favorable α_Zr/Hf under one feed acidity cannot be extrapolated to variable industrial liquors. The cost of extracting the bulk Zr inventory and subsequently stripping it must be incorporated into reagent intensity and recovery, alongside raffinate purity or the loaded-product pathway.

C. Hafnium-selective organophosphorus systems. Acidic organophosphorus extractants such as D2EHPA/P204, PC88A/P507, Cyanex-family reagents and dialkylphosphinic acids can favor Hf transfer in particular sulfate and chloride regimes (Banda et al., 2014; Lee et al., 2015; Wang et al., 2016b, 2016c, 2022, 2023; He et al., 2021; Han et al., 2026; Liu et al., 2026). Their appeal is Hf removal while retaining the larger Zr inventory, but extraction shifts with acidity, ligand concentration, load, and competing ions. Hf-rich stripping, Zr co-extraction, extractant aging, and acid or neutralization needs must be reported before claiming a net advantage. Mechanistic understanding (Vermaak et al., 2018; Dong et al., 2025) is necessary but does not replace stagewise closure.

D. Thiocyanate, ketone and synergistic systems. MIBK/HSCN-type systems and ketone homologs can generate strong preferential extraction, including newer MIBK–HSCN–glycine and DIBK-based formulations (Chen et al., 2026; Xiong et al., 2024; Zhao et al., 2024; Wu et al., 2019; Xu et al., 2012, 2016). Their assessment must jointly consider thiocyanate stability and decomposition risks, ketone volatility, flammability, solvent emissions, material compatibility, and downstream liquor purification. Aliquat 336 and TOPO-based thiocyanate variants (Wu et al., 2022) further illustrate that selectivity can be altered without resolving the industrial solvent-recovery burden. High single-contact separation is an initial screening metric rather than a qualified-product result.

E. Ion exchange and extraction chromatography. Ion-exchange and resin-based schemes (Felipe & Ladeira, 2018; Ma et al., 2019; Fan et al., 2022; Hu et al., 2025; Wang et al., 2025; Poernomo et al., 2026) may offer sharp selectivity or polishing opportunities,

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especially when volumes are manageable. The decisive design variables are working rather than nominal equilibrium capacity, breakthrough and displacement curves, bed regeneration, eluate concentration, resin lifetime, pressure drop, and continuous or cyclic throughput. Ion-imprinted membranes (Tang et al., 2023) and ligand-functionalized silica (Das et al., 2020) require similar durability and feed-matrix testing. Evidence based solely on batch adsorption cannot establish industrial replacement for multi-stage extraction.

F. Ionic liquids, membranes, MOFs, and emerging ligands. Task-specific ionic liquids (Pathak et al., 2021), new phosphinic extractants (Xie et al., 2026; Zhao et al., 2020), advanced sorbents, metal-organic framework composites (Yang et al., 2025), and ligand-specific molecular studies (Qi et al., 2026; Sommers et al., 2022) reveal opportunities for tailored Zr/Hf discrimination. However, synthesis complexity, selectivity in real mixed-metal matrices, sorbent or membrane life, solvent loss, scale-dependent kinetics, and regeneration can outweigh laboratory improvements. This is chiefly discovery-stage evidence until sustained continuous operation and life-cycle inventories are shown.

G. Industrial integration and product-qualification test. Across all families, comparative readiness requires actual loaded-liquor assays; steady or time-resolved stage count and phase ratios; total Zr yield; independent Hf removal and DF_Hf; final Hf/Zr and other impurity limits; scrubbing and stripping losses; reagent make-up and purge; and continuous-campaign stability. Mechanistic reviews by Dong et al. (2025) and Rodrigues et al. (2026) provide important chemistry context, but this framework adds harmonized qualified-product, TEA, LCA, circularity, and evidence gating. An experimental separation method is not equivalent to a deployable, nuclear-grade flowsheet until these conditions are documented.

## 6. Energy and Carbon Metrics

Energy accounting should use both thermal and electrical demand and explicitly distinguish delivered utility, primary energy, and electricity carbon intensity. Report GJ per tonne of qualified product and kWh per kilogram of zirconium as different—not interchangeable—metrics. For energy-intensive decomposition, heating duty, drying, reagent concentration, gas circulation, and thermal recovery may dominate different operating

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regimes. Gediga et al. (2019) provide upstream zircon-inventory context, whereas Yelatontsev et al. (2026) examine an alternative thermal conversion approach.

Plasma processing may intensify reaction zones but does not automatically reduce climate impact; the result depends on electricity supply, net specific energy, product yield, and avoided conventional operations. Molten-salt routes similarly require full electrochemical cell voltage, current efficiency, salt losses, and a product-refining boundary, not just ideal reversible electrolysis energy (Li et al., 2021; Mirza et al., 2023).

Scope 1 onsite combustion and reaction emissions, Scope 2 purchased energy, and relevant upstream material emissions should be shown without double counting. Carbon attribution changes materially with energy system and reagent recovery assumptions.

**Evidence-based comparison: Thermal and electrochemical burdens**

The studies discussed here identify distinct mechanisms, feeds, and operating boundaries. Their conclusions are not pooled quantitatively where product specifications, plant inventories, or experimental scales are incompatible.

Pereira (2026e) examines thermal decomposition of metal chlorides: Mechanisms, kinetics, gas–solid coupling, and metallurgical process integration—A critical review. Transferability to industrial process selection remains conditional on equivalent feed, product, and evidence quality.

**7. Reagent Circularity**

The true circularity indicator is avoided primary input per qualified product, not the percentage of liquor returned to a storage vessel. In alkaline processing, evaluate caustic recovery against sodium-bearing purge and silica accumulation; in chloride chemistry, HCl and chlorine recovery require contaminant and gas-closure accounting. Thermal chloride chemistry is process-specific, and decomposition or hydrolysis does not establish an industrial recovery loop without evidence of capture, concentration, and reuse.

Solvent extraction adds extractant deterioration, diluent losses, entrainment, and impurity buildup. Amaral et al. (2020), He et al. (2021), and Rozana et al. (2025) motivate reporting fresh makeup, recycle-to-purge ratio, stripping reagent, and solvent lifetime on a

JIRRS
Journal International Review of Research Studies
**Received:** 13/06/2026 - **Accepted:** 07/11/2026
**Vol**: 1.11
**DOI**: 10.66104/evz18e10
**Pages:** 1-37

product-normalized basis. Ion-exchange systems require analogous acid or alkali regeneration inventory (Jakóbik-Kolon & Bok-Badura, 2022).

An environmental burden can be transferred from spent reagent to saline liquid waste if recovery is not balanced by effective separation. A credible comparison therefore combines recovery fraction, recycle purity, purge rate, regeneration energy, and equipment constraints.

**Evidence-based comparison: Recovery, reagents, and secondary feedstocks**

The studies discussed here identify distinct mechanisms, feeds, and operating boundaries. Their conclusions are not pooled quantitatively where product specifications, plant inventories, or experimental scales are incompatible.

Davis et al. (2024) examine electrochemical decladding of used nuclear fuel; Han et al. (2020) examine electrochemical behavior and zirconium extraction on an Sn-coated W electrode in LiCl-KCl melts; Hur et al. (2021) examine separation of Zr from Zr-2.5Nb by electrorefining in LiCl-KCl for volumetric decontamination of CANDU pressure tubes. The process-level comparison must distinguish reclaimable metal from reagents that are genuinely regenerated in a closed circuit and account for contaminated secondary streams.

Jakóbik-Kolon et al. (2022) examine stripping hafnium and zirconium from chelating ion-exchange resin; Ji et al. (2021) examine sonochemical decontamination of magnesium and magnesium-zirconium alloys under mild conditions; Li et al. (2021) review the preparation of zirconium metal by electrolysis. The process-level comparison must distinguish reclaimable metal from reagents that are genuinely regenerated in a closed circuit and account for contaminated secondary streams.

Massot et al. (2024) examine zirconium metal recovery from Zircaloy in molten fluorides; Nevarez et al. (2021) examine zirconium recovery from Zircaloys using a hydrochlorination process; Pandey et al. (2016) examine recovery of Hf and Zr from slurry waste from a zirconium purification plant using solvent extraction. The process-level comparison must distinguish reclaimable metal from reagents that are genuinely regenerated in a closed circuit and account for contaminated secondary streams.

JIRRS
Journal International Review of Research Studies
**Received:** 13/06/2026 - **Accepted:** 07/11/2026
**Vol**: 1.11
**DOI**: 10.66104/evz18e10
**Pages:** 1-37

Pereira (2026a) examines conventional ion-exchange and chelating resins for metal recovery: A critical comparison of selectivity, dynamic performance, regeneration, and process integration; Sohn et al. (2021) examine computational model-based design of molten salt electrorefining process for high-purity zirconium metal recovery from spent nuclear fuel; Solem et al. (2024) examine electrochemical study of Zr from anodic dissolution using a consumable zirconium nitride anode. The process-level comparison must distinguish reclaimable metal from reagents that are genuinely regenerated in a closed circuit and account for contaminated secondary streams.

Sun et al. (2024) examine separation of Zr and Si in zirconium silicate by sodium hydroxide sub-molten salt; Takeda et al. (2018) examine zirconium metal production by electrorefining of Zr oxycarbide; Vestal et al. (2023) examine a novel protocol to recycle zirconium from zirconium alloy cladding from used nuclear fuel rods. The process-level comparison must distinguish reclaimable metal from reagents that are genuinely regenerated in a closed circuit and account for contaminated secondary streams.

Vutova et al. (2025) examine the impact of electron beam melting on the purification of recycled zirconium; Xu et al. (2016) examine zirconium and hafnium separation with molten salt extraction in Sn–Cu–Zr–Hf and Cu–Zr–Hf alloy systems; Zhang et al. (2022) examine the mechanism for electrochemical reduction of Zr(IV) in molten NaCl–KCl. The process-level comparison must distinguish reclaimable metal from reagents that are genuinely regenerated in a closed circuit and account for contaminated secondary streams.

## 8. Waste and Residue Metrics

Process mass intensity (PMI) expresses total process input mass per product mass, whereas E-factor expresses waste mass per product mass under an explicit boundary and accounting definition. They do not capture toxicity or radionuclide risk by themselves. Silica-rich residues, sodium salts, chloride brines, and spent organic materials require separate records of mass, composition, leachability, and treatment.

The mineral stream can carry naturally occurring radioactivity, complicating assumptions about unrestricted residue use. Studies of TENORM-reduced zirconia and zirconium sulfate (Amliliana & Muzakky, 2021; Samin et al., 2022) underscore why impurity

JIRRS
Journal International Review of Research Studies
**Received:** 13/06/2026 - **Accepted:** 07/11/2026
**Vol**: 1.11
**DOI**: 10.66104/evz18e10
**Pages:** 1-37

deportment belongs in the residue inventory, not only in product specifications. Concentrate-specific geochemical characterization remains necessary.

Water recirculation can reduce makeup while concentrating dissolved impurities; the resulting purge and treatment burden must be included. Compare alternative routes with residue characterization at equivalent final products rather than with unqualified ratios of solid-to-liquid separation efficiency.

## 9. CAPEX and OPEX Structure

Comparable techno-economic assessments (TEAs) should disclose, at a minimum, cost year, currency, geographic basis, annual nameplate capacity and utilization factor, project life, discount rate, contingency basis, equipment-cost scaling method, reagent make-up and stored inventories, solvent working inventory and replacement, materials of construction, maintenance, utility tariffs, waste treatment, and product-quality assurance. CAPEX must distinguish installed equipment, offsites, working capital, and contingency; OPEX must distinguish variable reagents/utilities from labor, maintenance, and waste-management costs. Cost normalization is invalid if chemical intermediate and nuclear-grade metal boundaries are mixed.

Market-based flowsheet rankings are highly conditional. A route with low single-pass reagent consumption may still require expensive solvent recovery, multistage contactors, or corrosion-resistant equipment. Conversely, a higher-temperature route may provide heat-integration opportunities at scale. Economic and environmental assessments of mineral feed conversion (Laghaei et al., 2025; Yelatontsev et al., 2026) are informative but should not replace site-specific capital-cost estimates.

Sensitivity must include feed grade, Hf content, Zr yield, purification rejection, reagent recycle, electricity tariffs, disposal prices, production scale, and required final purity. Without plant-level cost data, comparative statements must remain conditional rather than expressed as absolute commercial cost rankings.

JIRRS
Journal International Review of Research Studies
**Received:** 13/06/2026 - **Accepted:** 07/11/2026
**Vol**: 1.11
**DOI**: 10.66104/evz18e10
**Pages:** 1-37

## 10. Technology Readiness and Scale-Up Risk

Evidence levels are classified as industrial operation, demonstration, pilot, continuous laboratory, batch laboratory, thermodynamic/modeling, and conceptual. This qualitative ladder is not a numeric TRL assignment: a claimed TRL requires a clear technology definition and evidence of integrated operation in a relevant environment. Studies on novel resins and porous adsorbents are valuable mechanistic probes but typically lack a complete history of commercial impurity performance, uptime, and regeneration (Das et al., 2020; Hu et al., 2025; Yang et al., 2025).

For solvent extraction, transferability depends on continuous countercurrent campaigns, phase disengagement, scrubbing, and degradation. Electrochemical recycling faces challenges in current efficiency, cell materials, deposition morphology, and salt purification (Hur et al., 2021; Sohn et al., 2021; Massot et al., 2024). Laboratory demonstrations should be characterized as such, independently of their apparent recovery magnitude.

Table 3 is an evidence rubric rather than a judgment that a listed author has demonstrated a particular TRL. Process developers should report mass-closure uncertainty, repeatability, campaigns, uptime, and a product-qualified assay before asserting scale readiness.

**Table 3.** Evidence hierarchy for claims of process transferability

| Evidence | Minimum supporting record | Inference limitation |
|---|---|---|
| **Industrial** | Operating production, mass balance, quality control | Site-specific, not universal |
| **Demonstration or pilot** | Integrated campaigns and operating logs | Scale and uptime may differ |
| **Continuous laboratory** | Steady-state recovery and impurity tracking | Incomplete industrial environment |
| **Batch laboratory** | Repeatability under defined chemistry | No continuous operability proof |
| **Model or conceptual** | Assumptions, validation domain, uncertainty | Not a demonstrated TRL |

*Note.* Qualitative classification proposed here; no numerical TRL assigned to specific cited studies.

JIRRS
Journal International Review of Research Studies
**Received:** 13/06/2026 - **Accepted:** 07/11/2026
**Vol**: 1.11
**DOI**: 10.66104/evz18e10
**Pages:** 1-37

**Evidence-based comparison: Industrial readiness and scale limitations**

Scale-up comparisons are most informative when they connect reaction and separation mechanisms to continuous operation and independently reconciled streams. Studies of molecular extraction behavior inform mechanistic plausibility, but not commercial readiness by themselves.

Novaes et al. (2026) examine Hf(IV)/Zr(IV) extraction in sulfate media using experiments and molecular modeling; Pereira (2026b) reviews hafnium recovery across feedstocks. Such evidence helps prioritize solvent and speciation questions, while continuous-stage data remain necessary for an integrated readiness claim.

Pereira (2026d) discusses scale-up as a mechanism-preservation and flowsheet-transferability problem. In zirconium systems, this means testing losses, solvent degradation, phase disengagement, corrosion, and impurity accumulation as linked operations rather than extrapolating from a favorable bench-scale distribution ratio.

**11. Life-Cycle and Circularity Assessment**

LCA compares product-system impacts, whereas circularity metrics describe particular resource loops; they overlap but are not substitutes. A recycle fraction can be high while electricity consumption or hazardous brine generation increases. Gediga et al. (2019) characterize zircon-sand life-cycle effects; Liu et al. (2026) use an anthropogenic-flow framing that addresses a different system scale. Neither alone provides a complete cradle-to-gate comparison of nuclear-grade zirconium metal.

Recycling Zircaloy may reduce demand for fresh primary conversion but entails collection, decontamination, remelting or electrorefining, and radiological management. Vestal et al. (2023), Davis and Zhang (2024), and Pucciarelli et al. (2024) document distinct aspects of the secondary pathway. Results depend on avoided primary processing, secondary metal quality, recovery losses, and allocation rules.

Comparative environmental claims need identical functional units, temporal and geographic electricity scenarios, foreground process measurements, and uncertainty ranges.

JIRRS
Journal International Review of Research Studies
**Received:** 13/06/2026 - **Accepted:** 07/11/2026
**Vol**: 1.11
**DOI**: 10.66104/evz18e10
**Pages:** 1-37

The preferred boundary should disclose carbon intensity, freshwater use, reagent supply, solid residue, and hazardous-stream treatment as separate outputs.

**Evidence-based comparison: Environmental and circularity evidence**

Environmental evidence covers very different product systems. The relevant comparison must distinguish measured foreground inventories from conceptual circularity opportunities and should avoid treating all recycling studies as equivalent to nuclear-grade zirconium production.

Alqutaibi et al. (2025) review dental zirconia recycling, Gediga et al. (2019) quantify zircon-sand life-cycle burdens, and Laghaei et al. (2025) examine environmental impacts in a different process context. Their environmental conclusions depend on the specific feed, processing chain, and product specification.

Li et al. (2021) examine an electrochemical metal-production route, Liu et al. (2026) discuss anthropogenic zirconium flows, and Masry et al. (2026) address sustainability-related recovery. Process energy and stock-flow accounting complement each other but cannot replace one another.

Mukhachev et al. (2023) address resource efficiency in nuclear-grade production, whereas Pucciarelli et al. (2024) evaluate circular-economy strategies using life-cycle assessment. Their value for route screening depends on documenting consistent substitution, avoided burdens, and recycling quality.

Shu et al. (2026) examine selective sorption materials, while Vivoda (2026) examines the strategic and policy context for zirconium supply. A separation material can inform future process design, but policy relevance is not evidence of plant-level emissions reduction.

Zhao et al. (2024) investigate a modified porous sorbent for Zr(IV)/Hf(IV) separation. Environmental performance would additionally require sorbent lifetime, regeneration demand, secondary waste treatment, and the purity of recovered zirconium.

JIRRS
Journal International Review of Research Studies
**Received:** 13/06/2026 - **Accepted:** 07/11/2026
**Vol**: 1.11
**DOI**: 10.66104/evz18e10
**Pages:** 1-37

## 12. Multi-Criteria Decision Analysis and Uncertainty

Technical yield, Hf rejection, cost, carbon, water, circularity, and readiness cannot be collapsed into a transparent ranking without disclosing their normalization, gate conditions, and weights. First apply noncompensatory gates: required purity, feasible product form, regulatory safety, and evidence sufficiency. Then compare surviving flowsheets using Pareto analysis or an explicitly weighted multi-criteria decision analysis (MCDA). Figure 4 illustrates the order of evaluation.

Distinguish measured evidence from model outputs and assumed inventories. Monte Carlo propagation of feed assays, phase distribution factors, reagent recycle, energy, and pricing can reveal rank reversals, but assign no probability distribution without an empirical or justified basis. A practical stress test varies feed composition, solvent loss, Hf rejection, electricity mix, and disposal intensity rather than varying only a commodity price.

Critical gaps in the source corpus are integrated multi-stage balances with disclosed purification specifications, time-resolved reagent makeups, independent pilot reconciliation, and comparable CAPEX/OPEX/LCA data. The literature on hydrometallurgical Zr/Hf separation (Rodrigues et al., 2026; Dong et al., 2025) is richer than the literature demonstrating fully comparable cradle-to-gate systems.

Figure 4 presents the evidence-gated multicriteria decision framework proposed for zirconium process selection. It separates mandatory product-purity and evidence-quality thresholds from the subsequent comparison of product-qualified recovery, Zr/Hf separation, reagent and water circularity, energy and carbon intensity, costs, technological readiness, and uncertainty. The framework is conceptual and does not assign unverified performance values to individual routes.

JIRRS
Journal International Review of Research Studies
**Received:** 13/06/2026 - **Accepted:** 07/11/2026
**Vol**: 1.11
**DOI**: 10.66104/evz18e10
**Pages:** 1-37

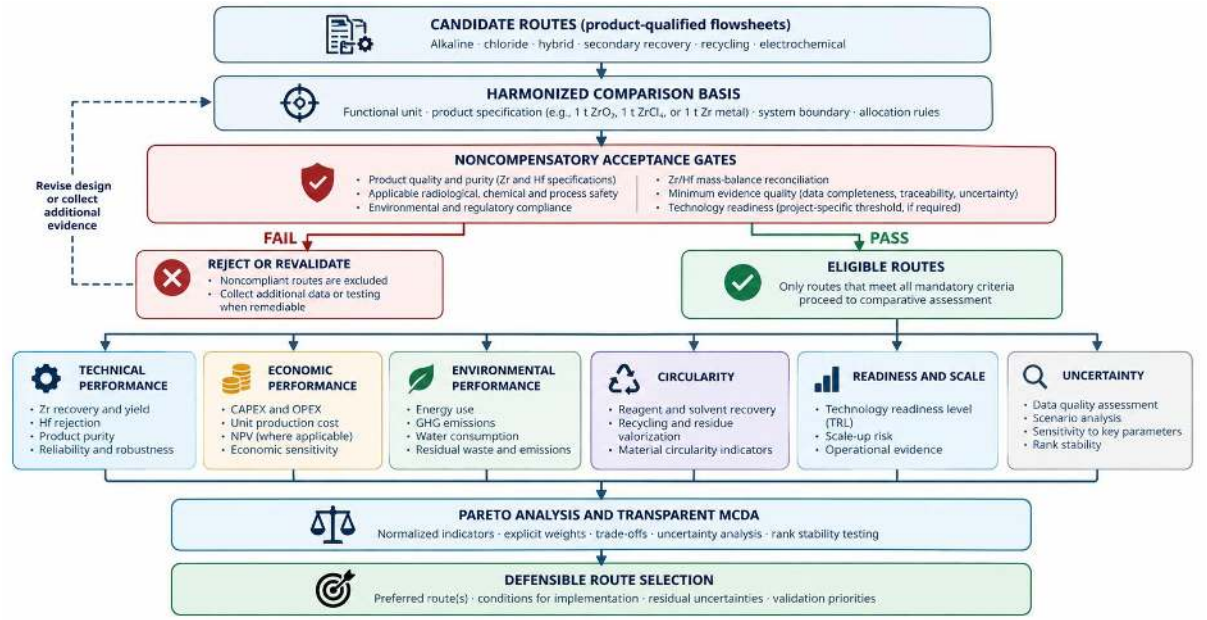



**Figure 4.** Evidence-gated multicriteria decision framework for zirconium process selection.
*Note.* Conceptual figure retained from the original manuscript; authorship and any third-party source permissions must be verified before submission.

**Evidence-based comparison: Multi-criteria uncertainty and research priorities**

The remaining evidence links specialized analytical or separation methods to uncertainties in the integrated assessment. These sources are retained for clearly delimited technical questions rather than assigned unsupported process-level economic outcomes.

Ali et al. (2023) examine zirconium preconcentration from raffinate using a polymer composite; Amliliana et al. (2021) concern low-TENORM zirconium sulfate preparation. Both topics highlight that impurity and residue criteria should be specified before selecting a performance metric.

Jiao et al. (2024) examine hafnium determination in zirconium, and Ma et al. (2026) examine deoxidation chemistry. Analytical detection capability and downstream oxygen removal are essential quality-control constraints, although neither alone establishes the economics of the preceding separation train.

## 13. Conclusions and Technology Roadmap

Compare zirconium technologies at the same qualified final product, with transparent feed characterization, complete mass and impurity balances, and consistent upstream and

JIRRS
Journal International Review of Research Studies
**Received:** 13/06/2026 - **Accepted:** 07/11/2026
**Vol**: 1.11
**DOI**: 10.66104/evz18e10
**Pages:** 1-37

downstream boundaries. Isolated zirconium recovery, an attractive equilibrium separation factor, or high recycled-liquor throughput cannot alone demonstrate commercial or environmental superiority.

The near-term roadmap is to harmonize reporting of Zr and Hf balances, material intensity, final impurity limits, and utility demands. The medium-term priority is pilot-scale integration of decomposition, separation, reagent regeneration, and product finishing with quantified uncertainty. Long-term decisions require site-specific cost models, cradle-to-gate environmental inventories, and evidence-gated multicriteria comparisons. Routes should advance on demonstrated combined performance rather than nominal laboratory yield.

## Declarations

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### Conflict of Interest

The author has not yet supplied a definitive conflict-of-interest declaration; this must be confirmed before submission.

### Data Availability

No new experimental data were generated for this literature-based manuscript. The author's bibliography underpins the synthesis.

### Author Contributions

The manuscript identifies a single author. Proposed CRediT roles for author confirmation: Conceptualization; Methodology; Investigation; Formal analysis; Writing – original draft; Writing – review and editing; Visualization.

## References

Abdel Moamen, O. A., Abu Elgoud, E. M., Masry, B. A., Gayed, H. M., El-Nadi, Y. A., & Borai, E. H. (2025). Efficient separation and purification of yttrium from zirconium onto anion exchange sorbent Amberlite A27 from acidic solution. Applied Water Science, 15, 136. https://doi.org/10.1007/s13201-025-02471-9

Ali, A. H. (2022). Production of highly purified zirconium oxide from zircon mineral leach liquor using bis-(2-ethylhexyl) phosphate as a promising extractant. Chemical Papers, 76, 6723–6734. https://doi.org/10.1007/s11696-022-02339-1

Ali, A. H., Abdo, S. M., & Dakroury, G. A. R. S. (2023). Zirconium preconcentration from zircon raffinate using gamma radiation–induced polymerization of reduced graphene

JIRRS
Journal International Review of Research Studies

**Received:** 13/06/2026 - **Accepted:** 07/11/2026
**Vol**: 1.11
**DOI**: 10.66104/evz18e10
**Pages:** 1-37

oxide composite. Environmental Science and Pollution Research, 30, 58330–58345. https://doi.org/10.1007/s11356-023-26485-5

Aliakbari, M., Saberyan, K., Noaparast, M., Abdollahi, H., & Akcil, A. (2014). Separation of hafnium and zirconium using TBP-modified ferromagnetic nanoparticles: Effects of acid and metal concentrations. Hydrometallurgy, 146, 72–75. https://doi.org/10.1016/j.hydromet.2014.03.002

Alqutaibi, A. Y., Hamadallah, H. H., Aloufi, A. M., Alharbi, A. T., Alaydaa, R. M., & Alghauli, M. A. (2025). Dental zirconia residuals recycling: Processes, applications, and future perspectives: A scoping review. *BMC Oral Health, 25*, 725. https://doi.org/10.1186/s12903-025-06093-0

Amaral, J. C. B. S., & Morais, C. A. (2016). Study of zirconium and hafnium separation by solvent extraction technique from nitric and hydrochloric solutions with acid, basic, and neutral extractants. World Journal of Engineering and Technology, 4, 138–150. https://doi.org/10.4236/wjet.2016.43D017

Amaral, J. C. B. S., & Morais, C. A. (2020). Equilibrium of zirconium and hafnium in the process of extraction with TBP in nitric medium – Influence on the Zr/Hf separation. Minerals Engineering, 146, 106138. https://doi.org/10.1016/j.mineng.2019.106138

Amaral, J. C., Souza, A. L., & Morais, C. A. (2020). Liquid-liquid separation of zirconium and hafnium from nitric liquor in order to obtain nuclear zirconium oxide using TBP as extractant. Chemical Engineering Communications, 207, 73–83. https://doi.org/10.1080/00986445.2019.1573170

Amliliana, R. A., & Muzakky, M. (2021). Synthesis of low TENORM zirconium sulfate from $ZrO(OH)_2$ with sulfuric acid. Indonesian Journal of Chemistry, 21(4), 842–851. https://doi.org/10.22146/ijc.60298

Banda, R., & Lee, M. S. (2015). Solvent extraction for the separation of Zr and Hf from aqueous solutions. Separation & Purification Reviews, 44(3), 199–215. https://doi.org/10.1080/15422119.2014.920876

Banda, R., Lee, H. Y., & Lee, M. S. (2012). Separation of Zr from Hf in hydrochloric acid solution using amine-based extractants. Industrial & Engineering Chemistry Research, 51(28), 9652–9660. https://doi.org/10.1021/ie3008264

Banda, R., Lee, H. Y., & Lee, M. S. (2013a). Separation of Zr and Hf from strong hydrochloric acid solution by solvent extraction with TEHA. Journal of Radioanalytical and Nuclear Chemistry, 295(2), 1537–1543. https://doi.org/10.1007/s10967-012-1941-5

Banda, R., Lee, H. Y., & Lee, M. S. (2013b). Separation of Zr from Hf in acidic chloride solutions by using TOPO and its mixture with other extractants. Journal of Radioanalytical and Nuclear Chemistry, 298(1), 259–264. https://doi.org/10.1007/s10967-012-2349-y

Banda, R., Min, S. H., & Lee, M. S. (2014). Selective extraction of Hf(IV) over Zr(IV) from aqueous $H_2SO_4$ solutions by solvent extraction with acidic organophosphorus-based

JIRRS
Journal International Review of Research Studies

**Received:** 13/06/2026 - **Accepted:** 07/11/2026
**Vol**: 1.11
**DOI**: 10.66104/evz18e10
**Pages:** 1-37

extractants. Journal of Chemical Technology & Biotechnology, 89, 1712–1719. https://doi.org/10.1002/jctb.4249

Botelho Junior, A. B., Espinosa, D. C. R., & Tenório, J. A. S. (2021). Selective separation of Sc(III) and Zr(IV) from the leaching of bauxite residue using trialkylphosphine acids, tertiary amine, tributyl phosphate and their mixtures. Separation and Purification Technology, 279, 119798. https://doi.org/10.1016/j.seppur.2021.119798

Branken, D. J., Lachmann, G., Krieg, H. M., & Bruinsma, D. S. L. (2010). Influence of KF and HF on the selectivity of Zr and Hf separation by fractional crystallization of $K_2Zr(Hf)F_6$. Industrial & Engineering Chemistry Research, 49(2), 797–808. https://doi.org/10.1021/ie900747k

Chandramohan, P., Biswas, S., Krishna Mohan, T. V., & Rufus, A. L. (2026). Novel methodology for zirconium-based alloy surface decontamination using alkali fusion method. Chemical Engineering Science. https://doi.org/10.1016/j.ces.2025.122386

Cheje Machaca, D. M., Juyo Salazar, R. B., de Carvalho, T. C., Espinosa, D. C. R., & Tenório, J. A. S. (2026). Extraction of Nb, Ta, Zr, and Hf from tin slags originating from cassiterite beneficiation. International Journal of Minerals, Metallurgy and Materials, 33, 1966–1979. https://doi.org/10.1007/s12613-025-3367-x

Chen, S., Li, Y., Tan, B., Qi, T., & Wang, Y. (2026). Highly efficient separation of hafnium over zirconium via a newly designed MIBK-HSCN-glycine extraction system. Solvent Extraction and Ion Exchange, 44(1), 31–52. https://doi.org/10.1080/07366299.2025.2600312

Chu, M. N., Truong, M. X., Nguyen, T. H. L., Do, T. H., Duong, T. T. A., Tran, T. K. N., Ngo, T. C. Q., Nguyen, T. T. L., Vu, T. H., & Pham, M. A. (2022). Purification and characterization of high-purity nano zirconia by liquid-liquid extraction using D2EHPA/p-xylenes. *Inorganics, 10*(7), 93. https://doi.org/10.3390/inorganics10070093

Conradie, E. W., van der Westhuizen, D. J., Nel, J. T., & Krieg, H. M. (2016). The separation of zirconium and hafnium from $(NH_4)_3Zr(Hf)F_7$ using amine-based extractants. Journal of the Southern African Institute of Mining and Metallurgy, 116(10). https://doi.org/10.17159/2411-9717/2016/v116n10a4

Conradie, E. W., Van der Westhuizen, D. J., Nel, J. T., & Krieg, H. M. (2018). The hafnium-selective extraction from a zirconium(hafnium) heptafluoride ammonium solution using organophosphorus-based extractants. Solvent Extraction and Ion Exchange, 36(7), 658–673. https://doi.org/10.1080/07366299.2018.1510812

Das, A., Chandrakumar, K. R. S., Paul, B., Chopade, S. M., Majumdar, S., Singh, A. K., & Kain, V. (2020). Enhanced adsorption and separation of zirconium and hafnium under mild conditions by phosphoric acid-based ligand-functionalized silica gels: Insights from experimental and theoretical investigations. Separation and Purification Technology, 239, 116518. https://doi.org/10.1016/j.seppur.2020.116518

JIRRS
Journal International Review of Research Studies

**Received:** 13/06/2026 - **Accepted:** 07/11/2026
**Vol**: 1.11
**DOI**: 10.66104/evz18e10
**Pages:** 1-37

Davis, B., & Zhang, J. (2024). Electrochemical decladding of used nuclear fuel. *Progress in Nuclear Energy, 173*, 105256. https://doi.org/10.1016/j.pnucene.2024.105256

Dong, J., Xie, Q., Chen, W., Wang, L., & Wang, L. (2025). Advances in zirconium/hafnium separation leveraging solution chemistry: Mechanisms and applications. Journal of Environmental Chemical Engineering, 13(6), 119771. https://doi.org/10.1016/j.jece.2025.119771

Eliwa, A. A. (2024). Efficacious recovery of zirconium and yttrium ions from effluents using a gamma-irradiated reduced graphene oxide polymeric composite. Journal of Inorganic and Organometallic Polymers and Materials, 34, 1150–1171. https://doi.org/10.1007/s10904-023-02872-w

Ene, A., Zakaly, H. M. H., Salem, A. R., Gouda, A. A., Althumayri, K., Alshammari, K. F., Awad, H. A., Issa, S. A. M., Alluhaybi, A. A., Zaki, S. A., Ibrahim, H. A., Gado, M. A., El-Sheikh, E. M., & Atia, B. M. (2022). A new partially phosphorylated polyvinyl phosphate (PPVP) composite: Synthesis and its potential for Zr(IV) extraction from an acidic medium. *Separations, 9*(11), 382. https://doi.org/10.3390/separations9110382

Fan, J., Duan, L., Wang, Y., Zhai, X., Chen, G., & Yu, G. (2022). Preparation of DMHMP Levextrel resin and separation of zirconium and hafnium by extraction chromatography in $HNO_3$-HCl mixture. Colloids and Surfaces A: Physicochemical and Engineering Aspects, 638, 128216. https://doi.org/10.1016/j.colsurfa.2021.128216

Felipe, E. C. B., & Ladeira, A. C. Q. (2014). Estudo da separação do par zircônio e háfnio por troca iônica. HOLOS. https://doi.org/10.15628/holos.2014.1769

Felipe, E. C. B., & Ladeira, A. C. Q. (2018). Separation of zirconium from hafnium by ion exchange. Separation Science and Technology, 53(2), 330–336. https://doi.org/10.1080/01496395.2017.1385624

Franco-Magalhães, A. O. B., & de Godoy, D. F. (2021). Applied mineralogy of zirconium minerals: A case study of alkaline intrusion in SE-Brazil. SN Applied Sciences, 3, 592. https://doi.org/10.1007/s42452-021-04597-2

Gediga, J., Morfino, A., Finkbeiner, M., Schulz, M., & Harlow, K. (2019). Life cycle assessment of zircon sand. The International Journal of Life Cycle Assessment, 24, 1976–1984. https://doi.org/10.1007/s11367-019-01619-5

Hagag, M. S., Mubark, A. E., Eliwa, A. A., & Abdel-Razik, A. M. (2024). Retrieval of zirconium ions from laboratory solutions using in situ gel-precipitated aluminum-based composite sorbents. Colloids and Surfaces A: Physicochemical and Engineering Aspects, 132921. https://doi.org/10.1016/j.colsurfa.2023.132921

Han, M., Song, J., Sun, H., Zhang, X., & Qi, T. (2026). Removal of Hf(IV) ions from Zr(IV) ions in sulfuric acid solution by solvent extraction with PC88A. Metals, 16(1), 67. https://doi.org/10.3390/met16010067

JIRRS
Journal International Review of Research Studies

**Received:** 13/06/2026 - **Accepted:** 07/11/2026
**Vol**: 1.11
**DOI**: 10.66104/evz18e10
**Pages:** 1-37

Han, W., Wang, W., Li, M., Wang, J., Sun, Y., Yang, X., & Zhang, M. (2020). Electrochemical behavior and extraction of zirconium on Sn-coated W electrode in LiCl-KCl melts. Separation and Purification Technology, 232, 115965. https://doi.org/10.1016/j.seppur.2019.115965

He, H., Xu, F., Li, Q., Dong, P., Zheng, J., Wu, C., He, Z., Qu, J., Xu, Z., Chi, R., & Wu, M. (2021). Separation of hafnium from zirconium in $HNO_3$ solution by solvent extraction with Cyanex572. Hydrometallurgy, 202, 105600. https://doi.org/10.1016/j.hydromet.2021.105600

Hu, C., Zhao, H., Sun, R., Yang, X., & Wang, J. (2025). Novel dialkylphosphinic acid-modified Merrifield resins: Synthesis, characterization, and their adsorption and separation behaviors for zirconium and hafnium. Separation and Purification Technology, 353, 128539. https://doi.org/10.1016/j.seppur.2024.128539

Hur, J., Jeong, S., Sohn, S., Park, J., & Hwang, I. S. (2021). Separation of Zr from Zr-2.5Nb by electrorefining in LiCl-KCl for volumetric decontamination of CANDU pressure tube. Applied Sciences, 11(9), 3790. https://doi.org/10.3390/app11093790

Ismail, Z. H., Rizk, S. E., Abu Elgoud, E. M., & Aly, H. F. (2025). Separation of hafnium from zircon leach solution using anion-exchange resin and production of high-purity zirconia for nuclear applications. Hydrometallurgy, 231, 106411. https://doi.org/10.1016/j.hydromet.2024.106411

Jakóbik-Kolon, A., & Bok-Badura, J. (2022). Stripping of hafnium and zirconium from chelating ion-exchange resin. Polyhedron, 224, 116023. https://doi.org/10.1016/j.poly.2022.116023

Ji, R., Virot, M., Pflieger, R., & Nikitenko, S. I. (2021). Sonochemical decontamination of magnesium and magnesium-zirconium alloys in mild conditions. *Journal of Hazardous Materials, 406*, 124734. https://doi.org/10.1016/j.jhazmat.2020.124734

Jia, J., He, Y., Liu, Y., Chen, Y., Sun, Y., & Wang, R. (2024). Interdiffusion behaviors and mechanical properties of the Zr–Hf system. Materials Characterization, 216, 114295. https://doi.org/10.1016/j.matchar.2024.114295

Jiao, X., Lv, X., Li, S., Lv, Z., & Song, J. (2024). Determination of hafnium in zirconium by spectrophotometry. Processes, 12(10), 2286. https://doi.org/10.3390/pr12102286

Kabangu, J. M., Lubbe, S., & Crouse, P. L. (2019a). Separation of zirconium and hafnium by extraction with 2-octanol. Chemical Engineering Transactions, 75, 631–636. https://doi.org/10.3303/CET1975106

Kabangu, J. M., Lubbe, S., & Crouse, P. L. (2019b). Solvent extraction of zirconium and hafnium with 1- and 2-octanol: A comparative study. Chemical Engineering Transactions, 75, 607–612. https://doi.org/10.3303/CET1975102

Kabangu, M. J., Lubbe, S. J., & Crouse, P. L. (2020). Extraction and separation of zirconium using 1-octanol. Mining, Metallurgy & Exploration, 37(1), 93–100. https://doi.org/10.1007/s42461-019-0089-z

JIRRS
Journal International Review of Research Studies

**Received:** 13/06/2026 - **Accepted:** 07/11/2026
**Vol**: 1.11
**DOI**: 10.66104/evz18e10
**Pages:** 1-37

Laghaei, M., Haque, N., Bruckard, W. J., Pownceby, M. I., & Masoumi, H. (2025). Environmental impact assessment of valuable heavy minerals production through sand separation processes using life cycle assessment. Minerals Engineering, 232, 109556. https://doi.org/10.1016/j.mineng.2025.109556

Lee, M. S., Banda, R., & Min, S. H. (2015). Separation of Hf(IV)–Zr(IV) in $H_2SO_4$ solutions using solvent extraction with D2EHPA or Cyanex 272 at different reagent and metal ion concentrations. Hydrometallurgy, 152, 84–90. https://doi.org/10.1016/j.hydromet.2014.12.005

Li, S., Che, Y., Shu, Y., He, J., Song, J., & Yang, B. (2021). Review—Preparation of zirconium metal by electrolysis. Journal of The Electrochemical Society, 168(6), 062508. https://doi.org/10.1149/1945-7111/ac0996

Li, S., Che, Y., Song, J., Shu, Y., He, J., Xu, B., & Yang, B. (2021). Preparation of zirconium metal through electrolysis of zirconium oxycarbonitride anode. Separation and Purification Technology, 274, 118803. https://doi.org/10.1016/j.seppur.2021.118803

Liu, J., Song, J., Qi, T., Zhang, C., & Qu, J. (2016). Controlling the formation of $Na_2ZrSiO_5$ in alkali fusion process for zirconium oxychloride production. Advanced Powder Technology, 27(1), 1–8. https://doi.org/10.1016/j.apt.2015.08.005

Liu, L., Bao, Y., Ji, H., Mei, Z., Li, R., Li, Y., Yuan, Z., & Chen, J. (2026). Toward a sustainable anthropogenic zirconium cycle: A global-to-national perspective. Resources, Conservation and Recycling, 108708. https://doi.org/10.1016/j.resconrec.2025.108708

Liu, R., Qu, J., Song, J., Qi, T., & Du, A. (2014). Analysis of water leaching and transition processes in zirconium oxychloride octahydrate production. Ceramics International, 40(1), 1431–1438. https://doi.org/10.1016/j.ceramint.2013.07.026

Liu, X., Li, H., Xu, C., Peng, X., Sun, G., Cui, Y., & Lu, P. (2026). Separation of Hf(IV) and Zr(IV) using di(p-tert-octylphenyl) phosphate in sulfuric acid medium. Journal of Radioanalytical and Nuclear Chemistry, 335, 4963–4976. https://doi.org/10.1007/s10967-026-10995-w

Loges, A., Manni, M., Louvel, M., Wilke, M., Jahn, S., Welter, E., Borchert, M., Qiao, S., Klemme, S., Keller, B. G., & John, T. (2024). Complexation of Zr and Hf in fluoride-rich hydrothermal aqueous fluids and its significance for high field strength element fractionation. Geochimica et Cosmochimica Acta, 366, 167–181. https://doi.org/10.1016/j.gca.2023.12.013

Lubbe, S. J., & Crouse, P. L. (2023). Zircon as feedstock for zirconium chemicals, ceramics, the metal and alloys: A review. *Suid-Afrikaanse Tydskrif vir Natuurwetenskap en Tegnologie, 42*(1), 43–63. https://doi.org/10.36303/SATNT.2023.42.1.963E

Ma, J., Li, C., Liu, Z., Li, G., Tian, Y., Zhang, C., Zhang, S., & Hou, X. (2026). Occurrence forms of zirconium in beneficiation and metallurgical products from an alkaline granite porphyry-type polymetallic deposit in Inner Mongolia. Hydrometallurgy of China, 45(3), 448–454. https://doi.org/10.13355/j.cnki.sfyj.2026.03.021

JIRRS
Journal International Review of Research Studies

**Received:** 13/06/2026 - **Accepted:** 07/11/2026
**Vol**: 1.11
**DOI**: 10.66104/evz18e10
**Pages:** 1-37

Ma, S., Yang, F., Tan, F., Xie, M., Yu, S., Xue, L., Li, Z., & Hu, T. (2021). Highly efficient and selective solvent extraction of zirconium and hafnium from hydrochloric acid solution including amic acid extractant. Separation and Purification Technology, 279, 119779. https://doi.org/10.1016/j.seppur.2021.119779

Ma, Y., Stopic, S., Huang, Z., & Friedrich, B. (2019). Selective recovery and separation of Zr and Hf from sulfuric acid leach solution using anion exchange resin. Hydrometallurgy, 189, 105143. https://doi.org/10.1016/j.hydromet.2019.105143

Ma, Z., Yan, G., Yan, X., Ding, H., Wu, G., Zhang, S., Zhang, J., Chen, W., & Wang, L. (2026). Mechanism of oxygen–chlorine potential interaction during the Ca/Y-mediated solid-state deoxidation of zirconium. Materials, 19(12), 2515. https://doi.org/10.3390/ma19122515

Masry, B. A., Abu Elgoud, E. M., Gayed, H. M., Borai, E. H., & El-Nadi, Y. A. (2026). Sustainable recycling and separation of yttrium and zirconium metal values through leaching and extraction insights. Journal of Material Cycles and Waste Management, 28(3), 1778–1789. https://doi.org/10.1007/s10163-026-02505-7

Massot, L., Gibilaro, M., Quaranta, D., Serp, J., & Chamelot, P. (2024). Zirconium metal recovery from Zircaloy in molten fluorides. *Materials Sciences and Applications, 15*, 559–571. https://doi.org/10.4236/msa.2024.1512037

Mirza, M., Abdulaziz, R., Maskell, W. C., Wilcock, S., Jones, A. H., Woodall, S., Jackson, A., Shearing, P. R., & Brett, D. J. L. (2023). Electrochemical processing in molten salts – A nuclear perspective. Energy & Environmental Science, 16, 952–982. https://doi.org/10.1039/D2EE02010F

Mondal, K., & Mayes, R. T. (2026). Recent advances in cladding material extraction from fuels in nuclear fuel cycles. Industrial & Engineering Chemistry Research, 65(4), 1915–1928. https://doi.org/10.1021/acs.iecr.5c03686

Mukhachev, A. P., Yelatontsev, D. O., & Shevchenko, V. H. (2023). Resource-saving and environmental protection in nuclear-grade zirconium and hafnium production. *Geo-Technical Mechanics, 164*, 135–144. https://doi.org/10.15407/geotm2023.164.135

Mukhachev, A., Yelatontsev, D., Kharytonova, O., & Grechanyuk, N. (2024). Production of neutron-absorbing zirconium-boron alloy by self-propagating high-temperature synthesis and its refining via electron beam melting. Alloys, 3(3), 232–245. https://doi.org/10.3390/alloys3030013

Nevarez, R. B., McNamara, B., & Poineau, F. (2021). Recovery of zirconium from Zircaloys using a hydrochlorination process. Nuclear Technology, 207(2), 263–269. https://doi.org/10.1080/00295450.2020.1757961

Novaes, P. A. de A., Mingote, R. M., Morais, C. A., Bertoli, A. C., & Duarte, H. A. (2026). Mechanistic insights into Hf(IV)/Zr(IV) extraction by D2EHPA in sulfate media: A DFT study supported by experiments with industrial sulfate liquors. ACS Omega, 11(34), 51721–51730. https://doi.org/10.1021/acsomega.6c06044

JIRRS
Journal International Review of Research Studies

**Received:** 13/06/2026 - **Accepted:** 07/11/2026
**Vol**: 1.11
**DOI**: 10.66104/evz18e10
**Pages:** 1-37

Nurhadini, N., Fabiani, V. A., Ndruru, S. T. C. L., & Kurniawan, W. B. (2025). Synthesis and characterization of zirconium oxychloride from Bangka and Belitung zircon sand. Jurnal Kimia Sains dan Aplikasi, 28(7), 362–367. https://doi.org/10.14710/jksa.28.7.362-367

Pandey, G., Mukhopadhyay, S., Renjith, A. U., Joshi, J. M., & Shenoy, K. T. (2016). Recovery of Hf and Zr from slurry waste of zirconium purification plant using solvent extraction. Hydrometallurgy, 163, 61–68. https://doi.org/10.1016/j.hydromet.2016.03.005

Pathak, S., Biswas, S., & Sengupta, A. (2021). Application of task-specific ionic liquid for the extraction of zirconium and hafnium. Journal of Molecular Liquids, 338, 116616. https://doi.org/10.1016/j.molliq.2021.116616

Pereira, A. C. (2026a). Conventional ion-exchange and chelating resins for metal recovery: A critical comparison of selectivity, dynamic performance, regeneration, and process integration. International Journal of Current Science Research and Review, 9(9), 4916–4945. https://doi.org/10.47191/ijcsrr/V9-i9-08

Pereira, A. C. (2026b). Recovery of hafnium from mineral and secondary resources: Separation chemistry, process intensification, electrochemical routes, and industrial perspectives (2015–2026). Journal International Review of Research Studies, 1(1). https://doi.org/10.66104/dm9swv79

Pereira, A. C. (2026c). Recovery of zirconium from primary and secondary resources: Chemistry, Zr/Hf separation, electrochemical routes, and industrial perspectives. Journal International Review of Research Studies, 1(9), 1–58. https://doi.org/10.66104/s3mdb246

Pereira, A. C. (2026d). Scale-up in mineral processing: From mechanism preservation to flowsheet-scale transferability—A critical review and the MINESCALE framework. Journal of Advanced Multidisciplinary Studies, 1(III), 661–694. https://doi.org/10.68050/JAMS.2026.800

Pereira, A. C. (2026e). Thermal decomposition of metal chlorides: Mechanisms, kinetics, gas–solid coupling, and metallurgical process integration—A critical review. Nexus Science Review, 1(05 - October), 1–29. https://doi.org/10.66104/kp64h285

Poernomo, H., Muzakky, Supriyatna, Y. I., & Pusporini, N. D. (2026). Separation of Zr–Hf from local $Zr(SO_4)_3^{2-}$ anion solution feed using the CAC prototype filled with Dowex-1X8 resin. Journal of the Indian Chemical Society, 103(2), 102417. https://doi.org/10.1016/j.jics.2026.102417

Pucciarelli, M., Palethorpe, S. J., Spencer, J., Banford, A., Lettieri, P., & Paulillo, A. (2024). Using life cycle assessment to quantify the environmental benefits of circular economy strategies in the nuclear industry. *Progress in Nuclear Energy, 168*, 105026. https://doi.org/10.1016/j.pnucene.2023.105026

Qi, X., Cheng, X., Duan, S., Duan, W., & Sun, T. (2026). Mechanism insight into the separation of zirconium and hafnium by dibenzoylmethane: Crystal structures,

JIRRS
Journal International Review of Research Studies
**Received:** 13/06/2026 - **Accepted:** 07/11/2026
**Vol**: 1.11
**DOI**: 10.66104/evz18e10
**Pages:** 1-37

spectroscopy, and theoretical calculations. Separation and Purification Technology, 137455. https://doi.org/10.1016/j.seppur.2026.137455

Raison, P. E., Pavel, C. C., Steinbrück, M., & Wiss, T. (2025). Zirconia-based matrices for actinide management in recycling LWR claddings. MRS Advances, 10, 2193–2199. https://doi.org/10.1557/s43580-025-01392-8

Rao, R. B., Mishra, B., & Singh, D. (2024). Recovery of rare earth element-bearing placer minerals. *Journal of Mining Science*, 175–182. https://doi.org/10.15372/FTPRPI20240118

Ravi Kanth, M. V. S. R., Pushpavanam, S., Narasimhan, S., & Murty, B. N. (2020). A thermodynamic model for reactive extraction of macro amounts of zirconium and hafnium with TBP. *Separation and Purification Technology, 240*, 116491. https://doi.org/10.1016/j.seppur.2019.116491

Rodrigues, G. de O., Carvalho, T. C. de, & Romano, D. C. (2026). A comprehensive review of hydrometallurgical methods for the extraction and separation of zirconium and hafnium. Mining, Metallurgy & Exploration, 43(2), 1471–1484. https://doi.org/10.1007/s42461-026-01491-6

Rozana, K., Dewi, A. K., Poernomo, H., Ningtyas, S. A., & Wijaya, K. (2025). Zr–Hf separation of zirconium oxychloride products using tributyl phosphate (TBP) in kerosene. Journal of the Indian Chemical Society, 102(4), 101627. https://doi.org/10.1016/j.jics.2025.101627

Rozana, K., Dewi, A. K., Poernomo, H., Oh, W.-C., & Wijaya, K. (2024). Separation of zirconium and hafnium from zirconium oxychloride (ZOC) synthesis of Kalimantan zircon sand concentrate using an extraction method with tributyl phosphate (TBP)-dodecane in a nitric acid medium. Korean Journal of Materials Research, 34(5), 247–253. https://doi.org/10.3740/MRSK.2024.34.5.247

Salahshoori, I., Hatami, A., & Seyfaee, A. (2020). Investigation of experimental results and D-optimal design of hafnium ion extraction from aqueous system using emulsion liquid membrane technique. Journal of the Iranian Chemical Society, 18(1), 87–107. https://doi.org/10.1007/s13738-020-02007-9

Samin, A., W., P., H., D., A., S., & Rozana, K. (2024). Synthesis of environmentally friendly zirconium oxide from zircon sand. Journal of Sustainable Metallurgy, 10(2), 903–913. https://doi.org/10.1007/s40831-024-00845-y

Samin, T., A., R., K., & Djati, F. K. (2022). Synthesis and characterization of TENORM-free nano zirconia from zircon sand. Journal of the Indian Chemical Society, 99(10), 100678. https://doi.org/10.1016/j.jics.2022.100678

She, C., Zhang, Z., Kuang, S., Li, Y., Huang, X., & Liao, W. (2017). Separation of zirconium from hafnium in sulfate medium using solvent extraction with a new reagent BEAP. Hydrometallurgy, 169, 607–611. https://doi.org/10.1016/j.hydromet.2017.04.001

Shu, K., Yu, K., Ma, G., He, P., Zhang, M., Li, Y., & Ma, L. (2026). Phosphonate-functionalized covalent organic frameworks-derived carbon aerogel for efficient

JIRRS
Journal International Review of Research Studies

**Received:** 13/06/2026 - **Accepted:** 07/11/2026
**Vol**: 1.11
**DOI**: 10.66104/evz18e10
**Pages:** 1-37

separation of Zr4+ and Hf4+. Separation and Purification Technology, 382, 136088. https://doi.org/10.1016/j.seppur.2025.136088

Singh, D., Mishra, B., Basu, S., & Rao, R. B. (2021). A novel process for production of high-purity zirconium oxychloride from zircon sand for bio-inert ceramics. Journal of The Institution of Engineers (India): Series D, 102, 243–248. https://doi.org/10.1007/s40033-021-00283-0

Sohn, S., Choi, S., Park, J., & Hwang, I. S. (2021). Computational model-based design of molten salt electrorefining process for high-purity zirconium metal recovery from spent nuclear fuel. *International Journal of Energy Research*. https://doi.org/10.1002/er.5724

Solem, C. K. W., Wang, Z., Osen, K. S., & Martinez, A. M. (2024). Electrochemical study of Zr from anodic dissolution using a consumable zirconium nitride anode. ECS Transactions, 114(6), 133–143. https://doi.org/10.1149/11406.0133ecst

Sommers, J. A., Palys, L., Martin, N. P., Fast, D. B., Amiri, M., & Nyman, M. (2022). Oxo-cluster-based Zr/Hf(IV) separation: Shedding light on a 70-year-old process. Journal of the American Chemical Society, 144(6), 2816–2824. https://doi.org/10.1021/jacs.1c13338

Song, J., Fan, J.-F., Liu, J.-C., Liu, R., Qu, J.-K., & Qi, T. (2020). A two-step zircon decomposition method to produce zirconium oxychloride: Alkali fusion and water leaching. Rare Metals, 39(4), 448–454. https://doi.org/10.1007/s12598-015-0537-y

Subuki, I., Mohsin, M. F., Ismail, M. H., & Mohamed Fadzil, F. S. (2020). Study of the synthesis of zirconia powder from zircon sand obtained from Zircon Minerals Malaysia by the caustic fusion method. Indonesian Journal of Chemistry, 20(4), 782–790. https://doi.org/10.22146/ijc.43936

Sun, H., Song, J., & Qi, T. (2024). Separation of Zr and Si in zirconium silicate by sodium hydroxide sub-molten salt. Metals, 14(6), 630. https://doi.org/10.3390/met14060630

Supriadi, H., Poernomo, H., Basuki, K. T., Astuti, W., Suyanti, S., Handini, T., Ayatillah, N. S., Taftazani, A., & Prameswara, G. (2025). Characterization and kinetics of low-TENORM zirconium oxychloride production from zircon sand. Transition Metal Chemistry, 50(3), 241–251. https://doi.org/10.1007/s11243-024-00620-8

Taghizadeh, M., Ghanadi, M., & Zolfonoun, E. (2011). Separation of zirconium and hafnium by solvent extraction using a mixture of TBP and Cyanex 923. Journal of Nuclear Materials, 412(3), 334–337. https://doi.org/10.1016/j.jnucmat.2011.03.033

Takeda, O., Suda, K., Lu, X., & Zhu, H. (2018). Zirconium metal production by electrorefining of Zr oxycarbide. Journal of Sustainable Metallurgy, 4(4), 506–515. https://doi.org/10.1007/s40831-018-0199-8

Tang, T., Yang, F., Xie, M., Xue, L., Jiang, Z., Xie, Z., Wang, K., Li, Z., Geng, L., & Hu, T. (2023). Highly efficient separation and enrichment of hafnium from zirconium oxychloride solutions by advanced ion-imprinted membrane separation technology.

JIRRS
Journal International Review of Research Studies
**Received:** 13/06/2026 - **Accepted:** 07/11/2026
**Vol**: 1.11
**DOI**: 10.66104/evz18e10
**Pages:** 1-37

Journal of Membrane Science, 668, 121237. https://doi.org/10.1016/j.memsci.2022.121237

Tian, S., Song, J., Sun, H., Zhao, C., Zhang, Z., Han, M., & Qi, T. (2025). Selective extraction of zirconium from sulfuric acid solutions at high concentration with trioctylamine (TOA). Metals, 15(5), 468. https://doi.org/10.3390/met15050468

Trisnawati, I., Prameswara, G., Sari, E. P., Prasetya, A., Mulyono, P., & Petrus, H. T. M. B. (2022). Roasting decomposition for phosphate separation from zircon tailings. Journal of Mining Science, 58(5), 830–838. https://doi.org/10.1134/S1062739122050143

Velasquez, C. P., Pinreddy, M., Dionne, P.-A., Montazerian, M., & Mauro, J. C. (2026). Zircon decomposition in glass melting furnaces: Experimental and thermodynamic approaches. *International Journal of Applied Ceramic Technology, 23*(2), e70160. https://doi.org/10.1111/ijac.70160

Vermaak, V., Krieg, H. M., De Beer, L., & Van der Westhuizen, D. (2018). Mechanistic study of hafnium and zirconium extraction with organophosphorus extractants. Solvent Extraction and Ion Exchange, 36(2), 150–161. https://doi.org/10.1080/07366299.2018.1431078

Vestal, B. K., Travis, J., Albert, A., Bruffey, S., McFarlane, J., Collins, E. D., Hunt, R. D., & Barnes, C. E. (2023). A novel protocol to recycle zirconium from zirconium alloy cladding from used nuclear fuel rods. Journal of Nuclear Materials, 578, 154339. https://doi.org/10.1016/j.jnucmat.2023.154339

Vivoda, V. (2026). The zirconium paradox: How Australia's critical minerals policy enables China's strategic materials. Mineral Economics. https://doi.org/10.1007/s13563-026-00647-6

Vutova, K., Stefanova, V., Manoilov, E., Mihailova, I., Naplatanova, M., & Iliev, P. (2025). The impact of electron beam melting on the purification of recycled zirconium. Metals, 15(11), 1273. https://doi.org/10.3390/met15111273

Vutova, K., Stefanova, V., Markov, M., & Vassileva, V. (2022). Study of the possibility of recycling of technogenic hafnium during electron beam refining. Materials, 15(23), 8518. https://doi.org/10.3390/ma15238518

Wang, J., Liu, H., Xu, W., Chang, Z., Wang, P., & Wang, H. (2023). Selective extraction of hafnium over zirconium with dialkylphosphinic acids from H2SO4 media. Journal of the Brazilian Chemical Society, 34(7), 1003–1012. https://doi.org/10.21577/0103-5053.20230014

Wang, J., Liu, H., Zhao, H., & Wang, H. (2022). Selective extraction of Hf over Zr by a novel extractant (n-octyl)(2,4,4′-trimethylpentyl)phosphinic acid (INET-1) from sulfuric acid media. Journal of Radioanalytical and Nuclear Chemistry, 332, 2473–2483. https://doi.org/10.1007/s10967-022-08463-2

Wang, J., Yang, X., Hu, C., Sun, R., & Xu, G. (2025). Adsorption and separation of zirconium and hafnium from sulfate media by a conveniently synthesized (2,4,4-trimethylpentyl)(2-methylpropyl)phosphinic acid-functionalized Merrifield resin: A

JIRRS
Journal International Review of Research Studies
**Received:** 13/06/2026 - **Accepted:** 07/11/2026
**Vol**: 1.11
**DOI**: 10.66104/evz18e10
**Pages:** 1-37

combined study of experiments and DFT calculations. Journal of Chromatography A, 1749, 465894. https://doi.org/10.1016/j.chroma.2025.465894

Wang, L. Y., & Lee, M. S. (2014). Separation of zirconium and hafnium from nitric acid solutions with LIX 63, PC 88A and their mixture by solvent extraction. Hydrometallurgy, 150, 153–160. https://doi.org/10.1016/j.hydromet.2014.10.009

Wang, L. Y., & Lee, M. S. (2015). Separation of Zr and Hf from sulfuric acid solutions with amine-based extractants by solvent extraction. Separation and Purification Technology, 142, 83–89. https://doi.org/10.1016/j.seppur.2015.01.001

Wang, L. Y., & Lee, M. S. (2016a). A review on the aqueous chemistry of Zr(IV) and Hf(IV) and their separation by solvent extraction. Journal of Industrial and Engineering Chemistry, 39, 1–9. https://doi.org/10.1016/j.jiec.2016.06.004

Wang, L. Y., & Lee, M. S. (2016b). Development of a separation process for the selective extraction of hafnium(IV) over zirconium(IV) from sulfuric acid solutions by using D2EHPA. Hydrometallurgy, 160, 12–17. https://doi.org/10.1016/j.hydromet.2015.11.013

Wang, L. Y., & Lee, M. S. (2016c). Solvent extraction reaction of hafnium(IV) from strong sulfuric acid solutions with D2EHPA and PC 88A. Separation Science and Technology, 51(5), 759–766. https://doi.org/10.1080/01496395.2015.1119841

Wang, L. Y., Lee, H. Y., & Lee, M. S. (2013). Solvent extraction of zirconium and hafnium from hydrochloric acid solutions using acidic organophosphorus extractants and their mixtures with TOPO. Materials Transactions, 54(8), 1460–1466. https://doi.org/10.2320/matertrans.M2013150

Wang, L. Y., Lee, H. Y., & Lee, M. S. (2015). Solvent extractive separation of zirconium and hafnium from hydrochloric acid solutions by organophosphorous extractants and their mixtures with other types of extractants. Chemical Engineering Communications, 202(10), 1289–1295. https://doi.org/10.1080/00986445.2014.921621

Widayat, W., Almaas Salwa, D. A., Hasanah, A., Nisa, K., & Saudale, J. M. P. (2024). Preparation of zirconia catalyst from zircon sand and catalytic testing for biodiesel production. *Reaktor, 24*(2), 36–40. https://doi.org/10.14710/reaktor.24.2.36-40

Wu, M., Dong, P., Wu, C., Zhang, Z., Chi, R., & Xu, Z. (2022). Separation of Hf(IV) from Zr(IV) in thiocyanate medium with ionic liquid Aliquat 336. Hydrometallurgy, 213, 105947. https://doi.org/10.1016/j.hydromet.2022.105947

Wu, M., He, H., Xu, F., Xu, Z., Zhang, W., He, Z., Qu, J., Chi, R., & Huang, L. (2019). High-efficiency and selective extraction of Hf over Zr with DIBK-P350 synergistic extraction system. Separation and Purification Technology, 212, 255–261. https://doi.org/10.1016/j.seppur.2018.11.043

Wu, M., Xu, F., Dong, P., Wu, H., Zhao, Z., Wu, C., Chi, R., & Xu, Z. (2022). Process for synergistic extraction of Hf(IV) over Zr(IV) from thiocyanic acid solution with TOPO and N1923. *Chemical Engineering and Processing: Process Intensification, 170*, 108673. https://doi.org/10.1016/j.cep.2021.108673

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**Vol**: 1.11
**DOI**: 10.66104/evz18e10
**Pages:** 1-37

Xie, M., Yang, F., Liu, R., Yang, L., Du, J., Lan, X., & Huang, M. (2026). Synthesis of novel aminomethyl phosphinic acid extractants and their use in the extraction and separation of zirconium and hafnium. Hydrometallurgy, 241, 106649. https://doi.org/10.1016/j.hydromet.2026.106649

Xiong, J., Li, Y., Zhang, X., Wang, Y., Zhang, Y., & Qi, T. (2024). The extraction mechanism of zirconium and hafnium in the MIBK-HSCN system. Separations, 11(4), 93. https://doi.org/10.3390/separations11040093

Xu, L., Xiao, Y., van Sandwijk, A., Xu, Q., & Yang, Y. (2015). Production of nuclear-grade zirconium: A review. Journal of Nuclear Materials, 466, 21–28. https://doi.org/10.1016/j.jnucmat.2015.07.010

Xu, L., Xiao, Y., van Sandwijk, A., Zhao, Z., Li, J., Xu, Q., & Yang, Y. (2016). Zirconium and hafnium separation with molten salt extraction in Sn–Cu–Zr–Hf and Cu–Zr–Hf alloy systems. Separation Science and Technology, 51(10), 1664–1674. https://doi.org/10.1080/01496395.2016.1170852

Xu, Z., Wang, L., Wu, M., Xu, Y., Chi, R., Li, P., & Zhao, J. (2016). Separation of zirconium and hafnium by solvent extraction using a mixture of DIBK and P204. Hydrometallurgy, 165, 275–281. https://doi.org/10.1016/j.hydromet.2016.01.032

Xu, Z.-G., Wang, L.-J., Wu, Y.-K., Chi, R.-A., Zhang, L., & Wu, M. (2012). Solvent extraction of hafnium from thiocyanic acid medium in DIBK-TBP mixed system. Transactions of Nonferrous Metals Society of China, 22(7), 1760–1765. https://doi.org/10.1016/S1003-6326(11)61384-8

Yadollahi, A., Saberyan, K., Torab-Mostaedi, M., Charkhi, A., & Pourjavid, M. R. (2018). Solvent extraction separation of zirconium and hafnium from nitric acid solutions using a mixture of Cyanex-272 and TBP. Radiochimica Acta, 106(8), 675–684. https://doi.org/10.1515/ract-2017-2897

Yang, L., Liu, R., Xie, M., & Yang, F. (2025). Construction of a MIL-101-DGA (MOF) coupling betaine hydrochloride system for the green and efficient separation of zirconium and hafnium. ACS Applied Materials & Interfaces, 17(16), 24369–24381. https://doi.org/10.1021/acsami.5c02082

Yang, T., Sun, G.-X., Qian, Y., Ma, J.-F., & Li, Y.-L. (2019). Separation of hafnium from zirconium in hydrochloric acid solution with di(2-ethylhexyl)phosphoric acid by solvent extraction. Nuclear Science and Techniques, 30(2), 22. https://doi.org/10.1007/s41365-019-0548-8

Yang, X., Hu, C., Wang, J., Li, Y., & Liu, X. (2025). Preparation, structures, and performance of extraction resins based on zirconium and hafnium separation with extraction chromatography. Chemical Industry and Engineering Progress, 44(10), 5991–6003. https://doi.org/10.16085/j.issn.1000-6613.2024-1443

Yelatontsev, D., Kenez, M., Mukhachev, A., & Azimi, G. (2026). Plasma processing as a green alternative for advanced treatment of zirconium minerals: Environmental and

JIRRS
Journal International Review of Research Studies
**Received:** 13/06/2026 - **Accepted:** 07/11/2026
**Vol**: 1.11
**DOI**: 10.66104/evz18e10
**Pages:** 1-37

economic impact assessment. Chemical Engineering Journal, Article 181701. https://doi.org/10.1016/j.cej.2026.181701

Yugeswaran, S., Ananthapadmanabhan, P. V., & Lusvarghi, L. (2015). Zircon dissociation in air plasma through a low-power transferred arc plasma torch. Ceramics International, 41(1), 265–273. https://doi.org/10.1016/j.ceramint.2014.08.068

Yugeswaran, S., Ananthapadmanabhan, P. V., Thiyagarajan, T. K., & Ramachandran, K. (2015). Plasma dissociation of zircon with concurrent in-flight removal of silica. Ceramics International, 41(8), 9585–9592. https://doi.org/10.1016/j.ceramint.2015.04.020

Zhang, X., Huang, J., Min, D., Wen, T., Shi, Z., & Yang, S. (2022). Mechanism for electrochemical reduction of Zr(IV) in molten NaCl–KCl. International Journal of Hydrogen Energy, 47(10), 6544–6551. https://doi.org/10.1016/j.ijhydene.2021.12.038

Zhao, F., Yu, K., Shu, K., Su, L., He, P., Ma, G., Tang, Z., Peng, H., & Li, Y. (2024). P507-modified magnetic porous carbon derived from metal-organic frameworks for efficient separation of zirconium(IV) and hafnium(IV). Separation and Purification Technology, 345, 127276. https://doi.org/10.1016/j.seppur.2024.127276

Zhao, H., Hu, C., Sui, N., Liu, X., & Wang, J. (2024). Evaluation of novel solvent extraction systems for Zr/Hf separation with MIBK homologs. Arabian Journal of Chemistry, 17(1), 105425. https://doi.org/10.1016/j.arabjc.2023.105425

Zhao, J., Sui, Y., Peng, X., Sun, G., & Cui, Y. (2020). A new diphosphonic acid extractant, N, N-n-octylamine di(methylene phenylphosphinic acid), for extraction and separation of zirconium and hafnium in hydrochloric acid. Journal of Radioanalytical and Nuclear Chemistry, 324, 339–348. https://doi.org/10.1007/s10967-020-07039-2

Zhao, J., Yang, T., Zhang, H., Sun, G., & Cui, Y. (2019). Preferential extraction of hafnium over zirconium with D2EHPA through selective complexation of organic acids. Journal of Radioanalytical and Nuclear Chemistry, 321(1), 333–339. https://doi.org/10.1007/s10967-019-06585-8