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Secondary Aluminum Dross and Salt Slag Treatment: A Critical Review of Integrated Value Recovery, Risk Control, And Industrial Readiness

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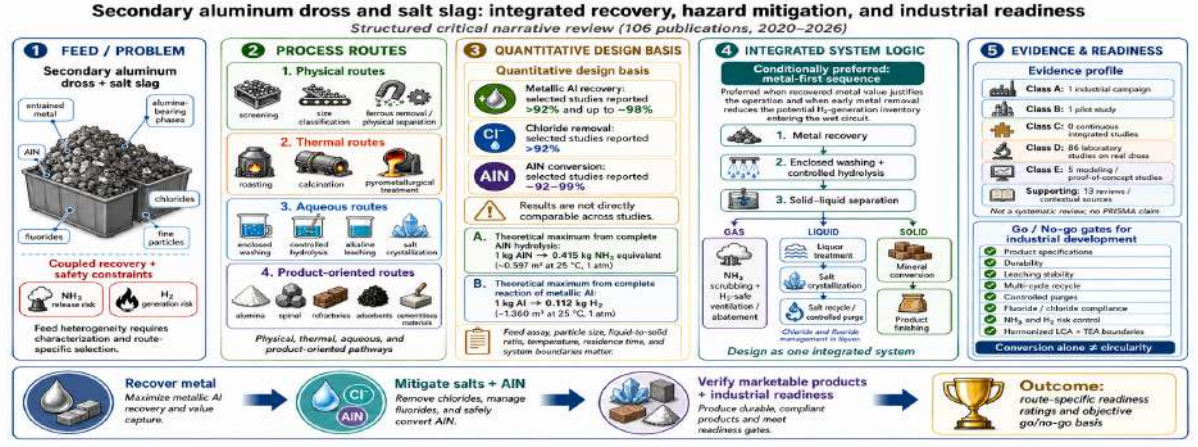
ABSTRACT: Secondary aluminum dross and salt slag are heterogeneous secondary resources whose entrained metal, alumina-bearing phases, aluminum nitride (AlN), chlorides, fluorides, and fine particles create coupled recovery and safety constraints. This structured critical narrative review maps 106 publications from 2020 to 2026 and evaluates physical, thermal, aqueous, and product-oriented routes without claiming systematic review or PRISMA compliance. Conservative evidence coding identified one industrial campaign (Class A), one pilot study (Class B), no continuous integrated Class C study, 86 laboratory studies on real dross (Class D), five modeling or proof-of-concept studies (Class E), and 13 supporting reviews or contextual sources. Selected studies reported metallic aluminum recovery above 92% and up to approximately 98%, chloride removal above 92%, and AlN conversion of 92.45–99.03%; these results are not directly comparable because of differences in feed assays, particle size, residence time, and system boundaries. A metal-first sequence is therefore conditionally preferred when the net value of recovered metal justifies the operation and when removal reduces the hydrogen inventory of the wet circuit. Stoichiometrically, 1 kg AlN can generate 0.415 kg NH_3 (0.597 m^3 at 25 °C and 1 atm), while 1 kg metallic Al can generate 0.112 kg H_2 (1.360 m^3) under complete reaction. Washing, controlled hydrolysis, salt crystallization, gas capture, and mineral conversion must consequently be designed as one integrated system. Laboratory production of alumina, spinel, refractories, adsorbents, or cementitious materials demonstrates conversion, not circularity, unless product specifications, durability, leaching stability, multi-cycle recycle, controlled purges, and harmonized life-cycle and techno-economic boundaries are verified. The review provides route-specific readiness ratings, quantitative design bases, and objective go/no-go gates for industrial development.

KEYWORDS: aluminum nitride, industrial readiness, secondary aluminum dross, salt slag, aluminum recovery, salt recycling.

Highlights

- The 106-publication evidence map is dominated by laboratory studies on real industrial dross.
- Metal-first processing is preferred only when recoverable metal value exceeds the added recovery cost.
- Each 1 wt% AlN and metallic Al in feed represents theoretical maxima of 5.97 m^3 NH_3/t and 13.60 m^3 H_2/t.
- Industrial readiness requires closed Al–Cl–N–F–water balances, stable recycles, and market-qualified products.

Graphical abstract



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1. INTRODUCTION

1.1 Relevance of secondary aluminum production

Aluminum recycling is a strategic component of low-carbon metals production because it retains the embodied value of alloyed metal and reduces dependence on primary extraction, refining, and smelting. The environmental advantage, however, is not automatic: secondary production shifts part of the burden from primary energy demand to scrap preparation, melt-loss control, flux use, air-emission control, and management of dross and salt slag. A circular assessment must therefore include both the recovered metal and the residues generated during melting, refining, transfer, skimming, and remelting. Recent reviews of secondary aluminum production and scrap recycling place dross control at the intersection of yield, alloy quality, resource efficiency, and environmental compliance (Padamata et al., 2021; Pereira, 2025; Wibner et al., 2021).

The practical importance of dross is amplified by its variable metal content. Every droplet that remains trapped in oxide films represents direct yield loss, while every kilogram of reactive nonmetallic fraction creates additional handling and treatment obligations. Dross treatment is consequently not a downstream waste-management activity alone; it is an extension of melt-shop metallurgical control and should be evaluated together with skimming practice, cooling rate, flux selection, and metal recovery (A. Meshram et al., 2021; Modalavalasa & Ayyagari, 2024; D. Wang et al., 2023; R. Wang et al., 2026).

1.2 Generation of secondary aluminum dross

Dross forms when liquid aluminum contacts oxygen and develops folded oxide skins that entrap metal, salts, refractory fragments, and alloy particles. Turbulent transfer, repeated skimming, long holding times, excessive superheat, and delayed cooling increase the opportunity for oxidation and metal entrapment. The resulting residue is not a single material: white dross is commonly associated with primary or low-salt operations and comparatively high metallic aluminum; black dross and salt slag contain larger proportions of flux salts and nonmetallic phases; secondary aluminum dross is often used more broadly for residues from recycling operations (Solem et al., 2023; Wibner et al., 2021; Padamata et al., 2021; Yuan et al., 2023).

The terminology can obscure process decisions. “Salt cake” may refer to the cooled product from rotary salt furnaces, whereas “fine dross” may denote the reactive fraction generated after crushing and screening. Because the same label can cover different metal, salt, and nitride contents, the treatment route should be selected from measured composition and phase distribution rather than residue name alone (Harmaji et al., 2024; Y. Liu et al., 2026; Modalavalasa & Ayyagari, 2024; Q. Wu et al., 2025).

1.3 Why the residue is simultaneously valuable and hazardous

The value of secondary dross derives from metallic aluminum, soluble NaCl–KCl fluxes, alumina-bearing phases, spinel-forming Mg and Al, and, in selected cases, trace or alloying elements. The hazard derives from the same chemistry: metallic aluminum can evolve hydrogen in alkaline aqueous systems; aluminum nitride hydrolyzes to ammonia; chlorides and fluorides create corrosive, saline liquors; and fine particles can react rapidly or become airborne. Hydrometallurgical treatment can transform these hazards, but it can also mobilize contaminants and create high-volume effluents when water and reagent loops are not closed (Y. Li et al., 2021; F. Liu et al., 2021; Q. Wu et al., 2025; X. Wu et al., 2025).

1.4 Knowledge gap

The literature contains many successful demonstrations of one step—metal separation, chloride washing, nitride conversion, aluminum extraction, precipitation, ceramic formation, or adsorption. Far fewer studies demonstrate all of the conditions needed for an industrially credible system: representative feed sampling, reconciled mass balances, safe gas management, reagent and water recycle, repeated salt reuse, market-grade product quality, stable residues, and validated economics. High extraction in a batch test can therefore coexist with low overall circularity if metal is oxidized, salts are discarded, ammonia is vented, or a low-value product merely dilutes contaminants (K. Huang & Yi, 2023; Y. Liu et al., 2026; D. (Wang et al., 2023; Xiao et al., 2023; Yeoh et al., 2026; P. Zhang et al., 2023).

1.5 Objectives and review questions

This review critically evaluates technologies for treating secondary aluminum dross and related salt slags with five linked objectives: maximize recovery of metallic and nonmetallic values; control aluminum nitride, hydrogen, salinity, fluoride, and dust hazards; identify product-quality requirements; compare environmental and economic burdens; and assess industrial readiness. The analysis asks how feed origin controls route selection, when physical separation should precede chemical conversion, how salts and

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nitrogen can be recovered, which products have credible markets, and what evidence is required to claim an integrated low-waste process.

2. REVIEW METHODOLOGY, EVIDENCE MAP, AND QUALITY ASSESSMENT

2.1 Review design

A structured critical narrative review combined with an evidence map was conducted. The article does not claim systematic review or PRISMA compliance because a database export, deduplication, and title/abstract screening log were not available for the author-curated corpus. Page et al. (2021) was used only to inform transparent reporting principles. All records in the closed corpus were nevertheless screened against predefined eligibility criteria and coded at study level in Supplementary Table S1.

2.2 Corpus construction and scope

The closed corpus contains 106 publications focused on secondary aluminum dross, black dross, salt slag, white dross, nonmetallic products, and associated recovery routes. It was assembled by the author through combinations of the terms "secondary aluminum dross," "black dross treatment," "salt slag recycling," "metallic aluminum recovery," "AlN hydrolysis," "salt recovery," "alumina recovery," "pyrometallurgical treatment," "hydrometallurgical treatment," "life cycle assessment," and "techno-economic analysis," supplemented by backward and forward citation chasing and publisher-metadata checks. The corpus covers 2020–2026 and was closed for this revision on 2 August 2026. Database-specific hit counts are not reconstructed and therefore not reported; this limitation is consistent with the chosen critical narrative review design.

2.3 Eligibility and study-level coding

A record was retained if it addressed dross generation or characterization, metallic Al recovery, salt or reactive-phase control, aluminum extraction and purification, product manufacture, environmental performance, or economics. Each record was coded for feed type, route, study type, scale, continuous or recycle operation, mass-balance closure, product qualification, and evidence class. Numerical outcomes were extracted only when the operating conditions and denominator were attributable to a specific study. Missing information was coded as NR (not reported) and was never imputed. Review papers were retained as supporting evidence but were not counted as primary process demonstrations.

2.4 Evidence hierarchy

Primary evidence was classified as follows: Class A, industrial campaigns or commercial operation; Class B, pilot or demonstration units; Class C, continuous or semicontinuous integrated testing; Class D, laboratory testing with real industrial dross; and Class E, simulation, synthetic material, or proof of concept. Reviews, method papers, and broad contextual sources were coded Supporting (S) rather than forced into A–E. When scale or continuity was ambiguous, the lower, more conservative class was assigned.

2.5 Critical appraisal criteria

Critical appraisal emphasized global rather than peak performance: feed grade, metallic Al and AlN assay methods, product purity, global yield, water and reagent demand, gas inventory and peak release rate, chloride and fluoride closure, secondary residues, internal recycle, repeated-cycle stability, and market acceptance. Claims such as "green," "harmless," or "zero waste" were downgraded when a study lacked an identified outlet for Al, Cl, N, F, Na, K, water, off-gas dust, or purge streams.

2.6 Corpus composition and thematic coverage

The evidence map identified 86 Class D studies, 5 Class E studies, 1 Class B study, 1 Class A industrial campaign, no Class C integrated study, and 13 Supporting sources. Route coding yielded 23 broad/context records, 21 reactive-phase-control studies, 15 aluminum-extraction/purification studies, 14 ceramics or construction studies, eight functional-product studies, eight salt-recovery/electrolysis studies, eight metal-recovery studies, five LCA/TEA studies, and four characterization/hazard studies. Figure 1(a) and Supplementary Table S1 make these distributions auditable.

Representative quantitative outcomes were extracted into Supplementary Table S2. Selected metal-recovery studies reported more than 92% and up to approximately 98% recovery under specific hot-extrusion, supergravity, or mechanically activated remelting conditions (Kudyba et al., 2021; Lan et al., 2026; Z. Wang et al., 2023a). Water washing removed more than 92% of chlorides from particles smaller than 2.8 mm at 30 wt% solids after 90 min at 25 °C (Teixeira et al., 2022). AlN-hydrolysis studies

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reported 92.45% conversion at 95 °C after 11.2 h and 99.03% nitride removal under catalyzed conditions at 96.6 °C after 2.85 h; the latter also removed 81.93% fluoride (Dong et al., 2023; Z. Li et al., 2023). These values are reported as conditioned observations rather than pooled estimates.

Aluminum-extraction studies cover water, acid, and alkaline leaching; alkali fusion and sintering; ammonium-sulfate roasting; Bayer-process integration; precipitation; and calcination (F. Chen et al., 2024; He et al., 2021; T. T. N. Nguyen et al., 2020; M. Shi et al., 2023; Türk et al., 2020). Product studies cover alumina, hydroxides, spinel, refractories, cements, geomaterials, adsorbents, zeolites, and MOFs, while five system studies address LCA, hybrid LCA, exergoeconomics, or TEA (Vallejo-Olivares et al., 2024; Xiao et al., 2023; Yeoh et al., 2026; P. Zhang et al., 2023; X. Zhu et al., 2020).

Study quality was heterogeneous. Feed sampling, direct metallic Al and AlN assays, uncertainty assessment, repeated recycle cycles, and full elemental balances were frequently absent. Accordingly, Supplementary Table S1 uses NR rather than assuming that an unreported recycle, balance, or commercial qualification was achieved.

2.7 Methodological limitations

The evidence map is complete for the closed 106-publication corpus, but it is not a database-level systematic review. Some classifications rely on metadata, abstracts, and accessible full text; ambiguous scale was coded conservatively. Heterogeneous feed assays and outcome definitions prevent meta-analysis. Quantitative comparisons are therefore presented as study-specific ranges with conditions, and no universal composition threshold is claimed. These limitations are reported explicitly rather than deferred to future data extraction.

Table 1 summarizes the executed critical-review protocol, the distribution of evidence, and the rules used to prevent overinterpretation.

Table 1. Executed review protocol, evidence coding, and quality controls

Component	Executed procedure	Output	Critical safeguard
Review design	Structured critical narrative review plus evidence map; corpus closed 2 August 2026	106 process publications; no PRISMA claim	No reconstructed database hit or exclusion count
Eligibility	Dross/salt-slag characterization, recovery, detoxification, products, LCA, or TEA	All retained records coded in Table S1	Reviews coded Supporting, not primary demonstrations
Study coding	Feed, route, scale, continuity/recycle, balance, product qualification	NR used when information was absent	No imputation of missing operating data
Evidence classes	A industrial; B pilot; C continuous integrated; D laboratory-real feed; E model/proof; S supporting	A=1; B=1; C=0; D=86; E=5; S=13	Ambiguous studies assigned the lower class
Quantitative synthesis	Study-specific values extracted with conditions and denominator	Representative results in Table S2	No pooled estimate across incompatible feeds

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Component	Executed procedure	Output	Critical safeguard
Readiness test	Balances, recycle stability, gas management, product specification, and market acceptance	Route-specific readiness in Table 11	Novelty or peak recovery does not imply readiness

Note. Developed by the author for this review. Page et al. (2021) reported only transparency principles; the review does not claim PRISMA compliance.

The protocol places greater weight on closed balances, repeated recycling, and qualified output than on an isolated recovery percentage. This prevents a laboratory conversion study from being interpreted as evidence of the elimination of industrial waste.

3. ORIGIN, CLASSIFICATION, AND PHYSICOCHEMICAL CHARACTERISTICS OF ALUMINUM DROSS

3.1 Formation mechanisms

Dross generation begins with rapid oxidation of liquid aluminum and the mechanical folding of oxide skins into the bath. Oxide films act as flexible cages that retain metal droplets, while magnesium and other alloying elements alter oxidation kinetics and phase formation. Contact–diffusion mechanisms can form aluminum nitride when aluminum-rich surfaces react with nitrogen-bearing atmospheres at elevated temperature. Residence time before cooling is therefore a metallurgical variable: it controls continued oxidation, coalescence, nitride formation, and the accessibility of metal during subsequent separation (J. Liu et al., 2025; Solem et al., 2023; Wibner et al., 2021).

3.2 Classification of residues

White dross generally contains more recoverable metal and less flux salt, while black dross and salt slag contain larger nonmetallic and soluble-salt fractions. Secondary dross may include remelting residues, salt-furnace products, and fines generated during crushing. These classes overlap, and each lot can contain metal-rich coarse particles, salt-rich fines, and refractory or spinel-rich fractions. A practical classification should therefore report at least metallic aluminum, water-soluble salts, AlN, particle-size distribution, and dominant mineral phases (Modalavalasa & Ayyagari, 2024; Padamata et al., 2021; Solem et al., 2023; Yuan et al., 2023).

3.3 Chemical composition

The main constituents are metallic Al, Al_2O_3 polymorphs, $MgAl_2O_4$, AlN, NaCl, KCl, MgO, SiO_2, Ca-bearing phases, Fe oxides, fluorides, and minor alloying or trace elements. The relative abundance determines both value and risk. High metallic Al favors immediate physical recovery; high salt content favors early washing and crystallization; high AlN requires controlled hydrolysis or thermal conversion; and high Mg–Al oxide content can support spinel or refractory products (Benkhelif & Kolli, 2022; K. Hu et al., 2021; M. Shi et al., 2022; C. Wang et al., 2026; Q. Wu et al., 2025).

3.4 Mineralogical and phase complexity

"Total aluminum" combines fundamentally different process responses. Metallic Al can be recovered or oxidized; alumina may be soluble or refractory depending on phase; spinel is more resistant to leaching; AlN releases ammonia on hydrolysis; and aluminum in silicates or complex salts may require roasting or fusion. Phase-transformation studies show why calcification, alkali roasting, ammonium-sulfate roasting, and molten-salt systems can change extraction behavior, but each transformation also redistributes nitrogen, chloride, and fluoride (F. Chen et al., 2024; Lei et al., 2022; H. Lv et al., 2022b; M. Xie et al., 2023a; Z. Zuo et al., 2025; Z. Zuo et al., 2023).

3.5 Particle-size distribution and liberation

Crushing and milling liberate aluminum droplets from oxide agglomerates, yet excessive comminution transfers metal and reactive compounds into fine fractions, increases dust, and complicates solid–liquid separation. Particle sorting, mechanical activation, and wet-stirred milling can improve subsequent metal or contaminant removal, but the optimum size is route-specific. A

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liberation curve that relates particle size to metallic Al, soluble salt, and AlN is more useful than a single bulk analysis (Guo et al., 2023; Kudyba et al., 2021; Z. Wang et al., 2023a; H. Xie et al., 2023a; Xue et al., 2022).

3.6 Variability and representativeness

Dross composition varies with scrap mix, alloy, furnace type, flux practice, temperature, skimming, cooling, and mechanical treatment. Representative sampling is difficult because dense metal pieces and fine salt-rich powder segregate rapidly. Industrial characterization should therefore use lot-based sampling, controlled subdivision, duplicate chemical and phase analysis, and reconciliation between size fractions. Without these steps, a small laboratory sample can overestimate recovery or understate gas generation (Solem et al., 2023; Wibner et al., 2021).

Table 2 links operational residue classes to the measurements and treatment priorities that should govern route selection.

Table 2. Dross types, dominant values, and principal risks

Residue class	Typical origin	Potential values	Principal risks	Priority characterization
White dross	Skimming with limited salt addition	High metallic Al; oxide fraction	Oxidation; H_2 in wet alkaline systems; hot-material hazards	Metallic Al by size; oxide phases; temperature history
Black dross	Secondary remelting with flux	Metallic Al; NaCl/KCl; alumina-rich fraction	NH_3, H_2, saline leachate, dust, F/Cl	Metallic Al, AlN, soluble salt, F, particle size
Salt slag/salt cake	Rotary salt furnace residue	Reusable salts; residual Al; mineral fraction	High salinity; reactive Al/AlN; corrosive fines	Salt composition, insolubles, metal, AlN, purge impurities
Processed fines	Crushing, screening, air classification	Concentrated oxides, salts, or AlN depending on cut	Dust explosibility; rapid hydrolysis; filtration difficulty	Size-resolved composition and gas-evolution tests
Washed nonmetallic residue	After water leaching	Alumina/spinel feed for products	Residual chloride, F, AlN, leachable metals	Residual salts, phase assemblage, aging and leaching

Note. Developed by the author based on industrial characterization and review studies (K. Hu et al., 2021; Modalavalasa & Ayyagari, 2024; Padamata et al., 2021; Solem et al., 2023; D. (Wang et al., 2023; Q. Wu et al., 2025; Yuan et al., 2023).

The table demonstrates why residue names should be treated as screening descriptors only. The same “black dross” label can require a metal-first, salt-first, or nitride-management-first route depending on measured partitioning across particle-size fractions.

Figure 1 combines the evidence distribution with the formation and classification of dross streams. The sampling gates show where process history and segregation must be preserved.

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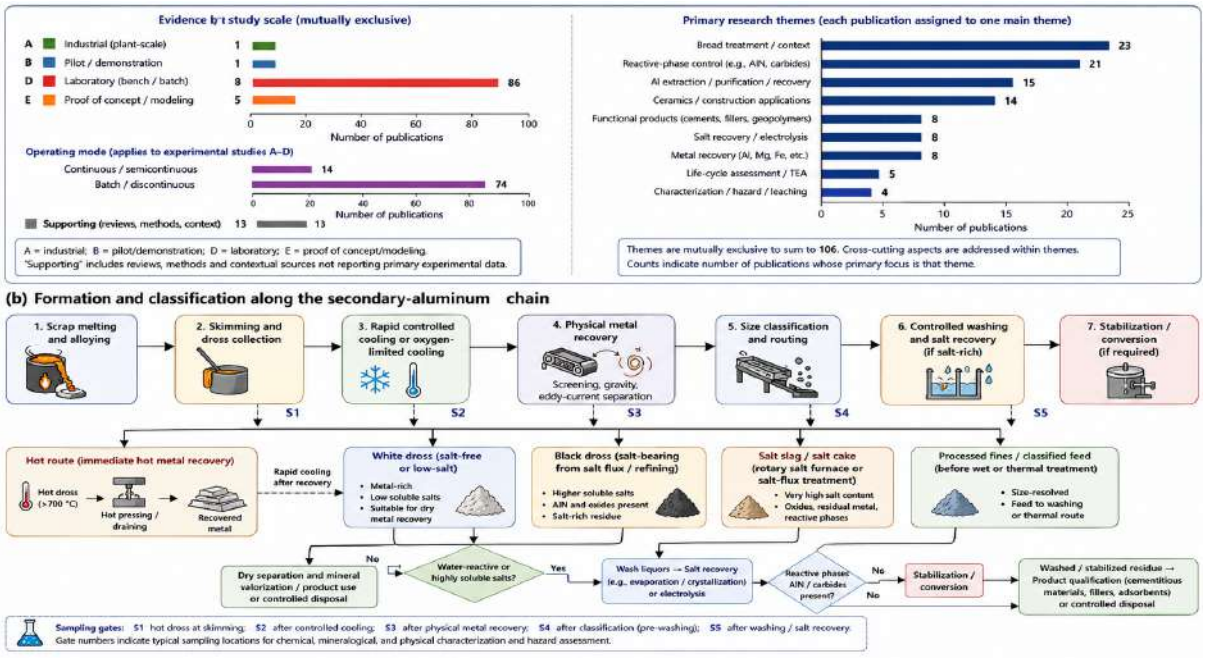

Figure 1. Evidence map and formation/classification of residues along the secondary-aluminum chain

Note. Developed by the author based on Solem et al. (2023), Wibner et al. (2021), Padamata et al. (2021), and the study-level evidence coding in Supplementary Table S1.

The evidence map exposes the central readiness gap: laboratory studies dominate and no integrated continuous Class C campaign was identified. The process chain also shows why a bulk "dross" sample cannot replace size- and stage-resolved characterization.

4. REACTIVITY, ENVIRONMENTAL RISKS, AND SAFE HANDLING

4.1 Aluminum nitride hydrolysis

Aluminum nitride is the defining aqueous-reactivity hazard of many secondary drosses. The overall reaction $AlN + 3H_2O \rightarrow Al(OH)_3 + NH_3$ gives a theoretical maximum of 0.415 kg NH_3 per kilogram of AlN, equivalent to 0.597 m^3 NH_3 at 25 °C and 1 atm. Thus, 1 wt% AlN in one tonne of feed represents 4.15 kg or 5.97 m^3 NH_3 before accounting for dissolution, retention, or incomplete conversion. The reaction releases heat and its rate depends on encapsulation, pH, temperature, particle size, agitation, and soluble ions (Dong et al., 2023; H. Lv et al., 2020; H.-L. Yang et al., 2022; Y. Zhang et al., 2023).

$AlN + 3H_2O \rightarrow Al(OH)_3 + NH_3\uparrow$

Reported AlN conversion illustrates the range of kinetic severity. Dong et al. (2023) obtained 92.45% at 95 °C after 11.2 h at a liquid-to-solid ratio of 7.8 mL/g and 400 rpm, with an apparent activation energy of 40.24 kJ/mol. Catalytic hydrolysis achieved 99.03% nitride removal at 96.6 °C after 2.85 h, with 9.28 mL/g and 12.62 wt% catalyst, along with 81.93% fluoride removal (Z. Li et al., 2023). These are batch results; reactor sizing must use the lot-specific peak gas-release rate, not final conversion alone.

4.2 Hydrogen generation

Residual aluminum may react when its protective film is disrupted. The simplified neutral-water expression $2Al + 6H_2O \rightarrow 2Al(OH)_3 + 3H_2$ gives 0.112 kg H_2 or 1.360 m^3 H_2 at 25 °C and 1 atm per kilogram of metallic Al. Therefore, 1 wt% reactive Al in one tonne of feed represents a theoretical 13.60 m^3 H_2. In strong caustic liquor, soluble aluminate species rather than solid $Al(OH)_3$ may predominate; the displayed reaction is a gas-inventory basis, not a complete speciation model.

$2Al + 6H_2O \rightarrow 2Al(OH)_3 + 3H_2\uparrow$

Hydrogen and ammonia can be generated concurrently. Closed wet-contact systems require controlled feed addition, heat removal, pressure relief, continuous $H_2/O_2/NH_3$ monitoring, ignition control, mist and dust removal, and an absorber or safe vent

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sized for the measured peak rate plus a conservative reaction inventory. Start-up, loss of agitation, blocked venting, power failure, hot-feed receipt, and accidental water ingress should be examined through HAZOP or an equivalent process hazard review.

4.3 Salt leaching and saline effluents

Water washing efficiently dissolves NaCl and KCl, but it creates a brine whose environmental burden depends on concentration, impurity load, and recovery strategy. Dilute washing can improve chloride removal while increasing evaporation duty and effluent volume. Countercurrent stages, high-solids operation, and reuse of mother liquor are therefore central to process design. Fluoride, sulfate, Ca, Mg, and fine solids can accumulate in the recycled brine and eventually require a controlled purge (Hegedüs et al., 2023; K. Hu et al., 2021; Teixeira et al., 2022; Q. Wu et al., 2025).

4.4 Dust and fine-particle hazards

Fine dross combines respirable mineral particles with reactive metal, nitride, and salts. Dry crushing, screening, and pneumatic conveying can generate dust clouds and segregate the most reactive fraction. Enclosed equipment, local extraction, conductive grounding, controlled humidity, and compatible dust collection are required. Baghouse dust should be characterized separately because its composition and hydrolysis rate may differ markedly from the bulk residue.

4.5 Leaching behavior and residue classification

Environmental stability must be assessed across relevant pH conditions and after aging, not only immediately after treatment. Washing can remove soluble chlorides while concentrating fluoride or trace metals in the solid; thermal treatment can immobilize some phases while volatilizing others; cementitious incorporation can reduce short-term leaching but fail if residual metal or AlN causes expansion. Geomaterial and co-thermal studies illustrate the need to combine mechanical performance with leaching and retention tests (Y. Lin et al., 2021; Muñoz-Vélez et al., 2023; Sun et al., 2024; C. Zhu et al., 2024).

4.6 Safe storage and preprocessing

Safe storage requires the segregation of hot, wet, and fine materials; the exclusion of rainwater; controlled cooling; ventilation; and NH_3/H_2 monitoring. Before scale-up, each feed family should undergo adiabatic or heat-loss-corrected reaction testing to determine induction time, temperature rise, total gas inventory, and peak evolution rate. For context, ammonia has an IDLH value of 300 ppm and a reported flammable range of approximately 15–28 vol%; these values are hazard references, not plant design limits (National Institute for Occupational Safety and Health [NIOSH], 2024).

4.7 Regulatory classification and product-status boundary

Intrinsic hazard and legal classification must be separated. Reactivity with water, NH_3/H_2 generation, salinity, fluoride, and dust are material properties, whereas hazardous-waste codes and product acceptance depend on jurisdiction and treatment status. In the European List of Waste, salt slags from secondary production (10 03 08*) and black drosses (10 03 09*) are hazardous entries; treatment residues may remain hazardous or move to a nonhazardous entry only after the applicable characterization demonstrates the change (European Commission, 2014).

A recovered stream should cease to be treated as waste only after it meets the relevant chemical, technical, leaching, durability, and market requirements. The article therefore uses “detoxification,” “stabilization,” or “hazard reduction” instead of “hazard-reduction treatment,” unless a specific regulatory determination is reported.

Table 3 summarizes the key reaction hazards to be addressed before selecting a wet, thermal, or product-oriented route.

Table 3. Quantitative hazard basis, initiating conditions, and required safeguards

Hazard / basis	Quantitative inventory or observation	Initiating conditions	Required safeguard	Verification
AlN hydrolysis	1 kg AlN → 0.415 kg NH_3 = 0.597 m^3 at 25 °C; 92.45–99.03% batch conversion reported	Moisture, warm liquor, fine particles, alkaline conditions	Metered wetting; closed agitated reactor; cooling; acid absorption; relief	Lot assay; induction time; peak NH_3 rate; temperature; pressure

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Hazard / basis	Quantitative inventory or observation	Initiating conditions	Required safeguard	Verification
Metallic-Al reaction	1 kg Al → 0.112 kg H_2 = 1.360 m^3 at 25 °C under complete reaction	Film disruption, high pH, elevated temperature	Metal-first recovery; H_2/O_2 monitoring; ignition control; safe vent/relief	Reactive-Al assay; peak H_2 rate; O_2; pH; pressure
Salt dissolution	>92% chloride removal reported at <2.8 mm, 30 wt% solids, 90 min, ~25 °C	Water contact with salt-rich porous fines	Countercurrent washing; corrosion-resistant materials; crystallization; purge	Cl, conductivity, Ca, Mg, F, sulfate, insolubles
Fluoride transfer	81.93% removal reported in one catalyzed hydrolysis study	Alkaline liquor or high-temperature volatilization	Solid–liquid–gas F balance; precipitation/sorption; off-gas capture	F in product, liquor, purge, dust, condensate
Dust event	No universal explosibility value; composition is lot-specific	Dry grinding, screening, pneumatic transfer	Enclosure, extraction, bonding/grounding, compatible collector, dust testing	Kst/Pmax or equivalent test where applicable; dust loading; Al/AlN
Abnormal operation	Gas and heat can continue after feed interruption	Loss of agitation/cooling, blocked vent, hot or wet feed	HAZOP; fail-safe feed isolation; emergency quench only if validated; relief disposal	Cause-and-effect test; alarm/interlock proof; emergency drill

Note. Developed by the author from stoichiometric calculations and reported results in Dong et al. (2023), Z. Li et al. (2023), Teixeira et al. (2022), Y. Li et al. (2021), and NIOSH (2024). Gas volumes are ideal-gas values at 25 °C and 1 atm and are not substitutes for measured peak rates.

The same wet-contact step can dissolve salt, hydrolyze nitride, and generate hydrogen. The design must therefore address material, gas, heat, pressure-relief, and abnormal-operation cases within a single process-safety basis.

5. PHYSICAL AND MECHANICAL RECOVERY OF METALLIC ALUMINUM

5.1 Cooling and oxidation control

Metal recovery begins before crushing. Rapid, controlled cooling limits continued oxidation and fixes the distribution of metal droplets, whereas prolonged exposure of hot dross to air consumes recoverable aluminum. Pressing, squeezing, or supergravity separation while the dross remains hot can promote droplet coalescence and remove metal before brittle oxide and salt phases are generated. The economic value of these steps is often greater than that of later chemical recovery because they preserve aluminum as metal (Lan et al., 2026; Z. Wang et al., 2023a; Z. Wang et al., 2023b).

5.2 Crushing, milling, and classification

After cooling, staged crushing and screening can separate coarse metal-rich particles from finer oxide- and salt-rich fractions. Mechanical activation can liberate metal, but overgrinding increases oxidation, dust, and entrainment of metallic fines in the nonmetallic product. The preferred flowsheet uses progressive size reduction with metal removal after each stage, supported by size-by-assay data. Mechanically activated phase separation and simultaneous Al/AlN separation demonstrate the potential of this approach (Kudyba et al., 2021; Xue et al., 2022).

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5.3 Gravity and density-based separation

Density differences between aluminum metal and porous oxide–salt agglomerates can be exploited by dry gravity, ballistic, or supergravity systems. Separation efficiency falls when metal droplets are encapsulated, oxidized, or present as thin flakes. Supergravity is particularly attractive for hot or molten systems because it enhances coalescence and phase separation without first converting valuable metal into a leachable compound (Lan et al., 2026; Z. Wang et al., 2023a; Z. Wang et al., 2023b).

5.4 Eddy-current and sensor-based separation

Eddy-current and conductivity-based sorting can recover liberated metallic particles from dry streams, while optical or sensor-based systems can reject refractory fragments and foreign inclusions. Their usefulness depends on particle size, shape, moisture, and the contrast between metal and composite particles. These technologies should be evaluated as polishing steps after controlled liberation rather than as substitutes for representative characterization.

5.5 Hot dross processing and remelting

Hot processing reduces the time available for oxidation and can return metal directly to production. Rotary converters, presses, and extrusion-assisted systems differ in salt demand, metal quality, energy use, and residual slag composition. Simple NaCl additions can improve coalescence in selected converter operations, while ultrasonic assistance has been explored to recover metal and produce Al–Si alloys from black dross (Illés & Kékesi, 2023; Taha et al., 2020). The operational trade-off is between immediate metal recovery and the generation of a salt-rich secondary residue requiring further treatment.

5.6 Performance indicators

Physical recovery should be reported through metal recovery, concentrate grade, residual metallic Al in the nonmetallic fraction, oxidation loss, energy consumption, and fines generation. Global yield must account for the metal remaining in dust, undersize, and remelting slag. A process that produces a high-grade concentrate from a small mass fraction can still leave substantial aluminum in the residue.

Table 4 compares physical options according to the mechanism that creates value and the limitations that determine scale-up.

Table 4. Physical metal-recovery technologies, representative performance, and evidence strength

Technology	Best feed condition	Representative outcome in corpus	Value proposition	Scale-up limitation	Evidence assessment
Hot pressing/squeezing	Fresh hot dross with high free-metal content	No harmonized yield reported in the coded corpus	Preserves Al as metal before oxidation	Rapid logistics, heat-safe equipment, variable rheology	Mature unit operation; route data incompletely reported
Hot extrusion + supergravity	Hot dross with dispersed droplets	>92% extraction reported by Lan et al. (2026)	Coalescence before cooling; low wet-process burden	Specialized hot equipment and feed variability	Class D in corpus; promising, not integrated pilot
Mechanical activation + remelting	Cooled composite particles	Up to ~98% recovery reported by Kudyba et al. (2021)	Liberation followed by direct metal return	Grinding energy, oxidation, fines, remelt losses	Class D
Mechanical activation + supergravity	Metal droplets trapped in oxide/salt matrix	97.14% metallic-Al recovery reported by Z. Wang et al. (2023a)	High separation without dissolving metal	Laboratory apparatus; scale and hot handling	Class D

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Technology	Best feed condition	Representative outcome in corpus	Value proposition	Scale-up limitation	Evidence assessment
Staged crushing/screening	Cooled dross with coarse liberated metal	Outcome must be reported by size-by-assay; no pooled value	Simple and compatible with dry circuits	Overgrinding, dust, metal loss to fines	Commercial component; study-level closure often NR
Ultrasonic-assisted recovery	Molten or semi-molten metal-bearing dross	Metal and Al–Si alloy production demonstrated	Can improve coalescence and inclusion release	Transducer durability, acoustic scale-up, energy	Class D / pilot claim not established in corpus

Note. Developed by the author based on Kudyba et al. (2021), Lan et al. (2026), Taha et al. (2020), Z. Wang et al. (2023a, 2023b), and Xue et al. (2022). Reported percentages are study-specific and are not pooled.

The comparison supports a conditional metal-first principle. Physical recovery should precede wet treatment when incremental recovered-metal revenue exceeds recovery cost, the feed contains liberated or liberatable metal, and removal materially reduces wet-circuit H_2 risk. Low-metal, salt-rich, or nitride-rich fines may instead enter a salt- or risk-management-first route.

Figure 2 presents the conditional metal-first sequence from cooling through hot recovery, staged comminution, classification, dry polishing, and transfer of the nonmetallic fraction.

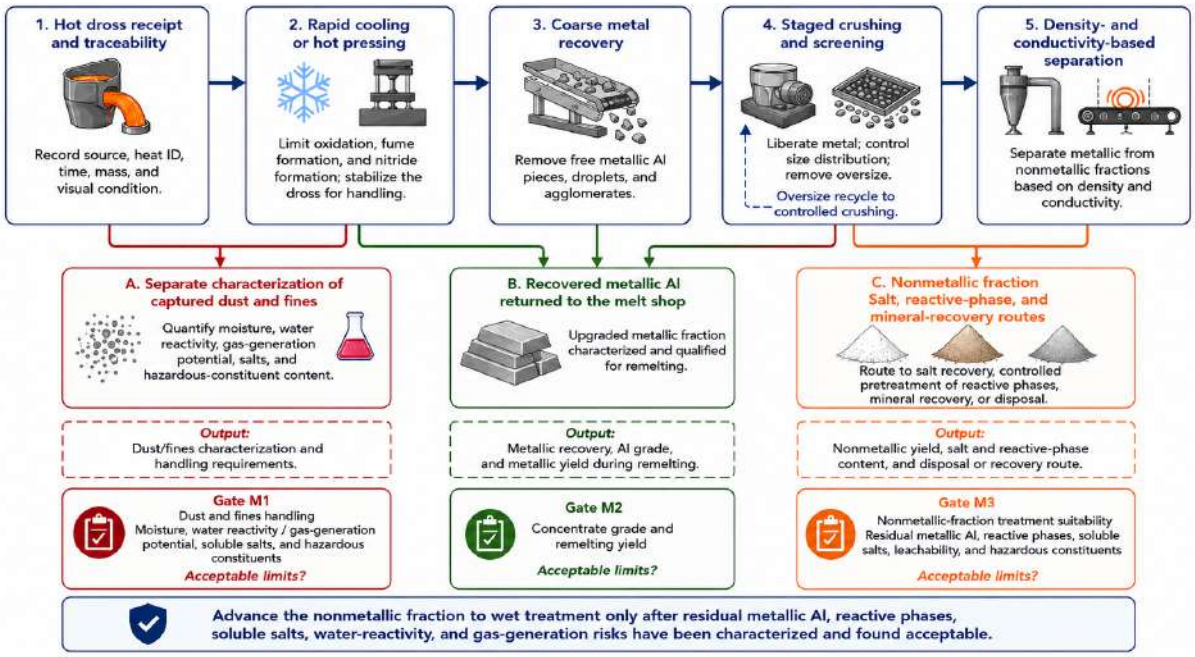

Figure 2. Metal-first preparation and recovery sequence for secondary aluminum dross

Note. Developed by the author based on Illés and Kékesi (2023), Kudyba et al. (2021), Lan et al. (2026), Taha et al. (2020), Z. Wang et al. (2023a, 2023b), and Xue et al. (2022).

Oversize, captured dust, recovered metal, and residual-metal assay are explicit control points. Hot and cooled operations remain separate because their oxidation losses and safety requirements differ.

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6. PYROMETALLURGICAL ROUTES AND SALT-ASSISTED METAL RECOVERY

6.1 Rotary salt furnaces

NaCl–KCl fluxes protect metal droplets from oxidation, reduce interfacial barriers, and support coalescence and metal–oxide separation in rotary furnaces. Their benefit is offset by the production of salt slag containing soluble salts, residual metal, oxides, AlN, and fluoride. The furnace should therefore be evaluated as the first stage of a closed salt cycle, not as a complete dross solution. Flux composition, salt factor, temperature, residence time, and slag tapping practice determine both metal yield and downstream salt-recovery load (Illés & Kékesi, 2023; Padamata et al., 2021; Padilla et al., 2022).

6.2 Tilting rotary furnaces and low-salt operation

Tilting and optimized rotary systems can reduce salt use and improve control of the metal pool. Low-salt operation is attractive when it lowers salt-slag generation without sacrificing metal recovery, but reduced flux can increase oxidation or produce a viscous slag that retains droplets. A valid comparison must include metal yield, specific salt consumption, furnace productivity, off-gas treatment, and the residual metal content of the slag.

6.3 Plasma and salt-free technologies

Salt-free thermal technologies avoid soluble-salt residues but typically demand more energy and tighter control of oxidation and refractory wear. Their environmental advantage depends on the electricity or fuel mix, metal recovery, and off-gas composition. They are most credible where disposal costs are high, heat recovery is available, and salt-recovery infrastructure is absent. Without these boundary conditions, the absence of salt does not guarantee lower life-cycle impact.

6.4 Thermal oxidation and calcination

Calcination and roasting can convert AlN, residual metal, carbides, and volatile salts into more stable phases. Pyrometallurgical removal of AlN and multipollutant conversion have been studied through direct roasting, additive-assisted roasting, vacuum distillation, and thermal preparation of corundum (R. Li et al., 2024; S.-S. (Lv et al., 2022; Qu et al., 2023; J. Wang et al., 2021; M. Xie et al., 2023b; J. Yang et al., 2024; X. Zhu et al., 2022). The temperature must be high enough for conversion yet controlled to avoid sintering, which reduces leachability or product reactivity.

6.5 Sintering and phase transformation

Alkaline sintering, calcification, ammonium-sulfate roasting, and alkali fusion transform refractory Al-bearing phases into soluble aluminates or sulfate-derived intermediates. These routes can increase aluminum recovery and remove harmful components, but they introduce reagents, solid additives, and thermal duty. Phase-transformation studies indicate that selectivity depends on the conversion of alumina and spinel relative to silica, Mg, Fe, fluoride, and nitride (F. Chen et al., 2024; Deng et al., 2024; He et al., 2021; Lei et al., 2022; H. Lv et al., 2022b; Wajima, 2020; Wei et al., 2023; M. Xie et al., 2023a).

6.6 Air emissions and thermal integration

Thermal treatment can release particles, chlorides, fluorides, ammonia or nitrogen species, and acid gases. Off-gas trains may require cyclones, filters, scrubbers, condensers, or fluoride capture, and the recovered dust must be accounted for in the material balance. Heat recovery from hot solids or gases can improve energy performance, while drying wet residues before calcination can dominate fuel use. Thermal routes should therefore report both direct conversion and the full gas-cleaning and heat-integration system.

Table 5 compares the principal thermal strategies by their metallurgical function and the burden they impose on downstream treatment.

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Table 5. Pyrometallurgical routes, products, and environmental trade-offs

Route	Primary purpose	Typical product	Main advantage	Main burden / emission	Critical scale-up variable
Rotary salt furnace	Recover metallic Al	Metal + salt slag	Established coalescence and throughput	Salt-slag generation, dust, chloride-bearing gas	Salt factor and residual Al in slag
Low-salt tilting furnace	Reduce flux while recovering metal	Metal + lower-salt slag	Lower soluble residue per tonne	Possible oxidation and poor separation	Slag fluidity and heat transfer
Salt-free / plasma	Thermal separation without flux	Metal + oxidized mineral residue	Avoids NaCl/KCl addition	High energy, refractory wear, oxidation	Energy source and metal yield
Roasting/calcination	Destroy AlN and residual reactivity	Detoxified oxide-rich solid	Improves safety and product stability	Volatile Cl/F, dust, fuel demand	Gas cleaning and conversion uniformity
Alkaline or ammonium roasting	Transform Al into soluble phase	Leachable aluminate/sulfate intermediate	Higher extraction from refractory phases	Reagent recovery and impurity migration	Reagent ratio and recycle
Molten-salt electrolysis	Recover alloy or valuable elements	Al alloy/electrolyte system	Potential high-value metal production	Electrolyte control, energy, impurity buildup	Bath chemistry and phase stability

Note. Developed by the author based on Teixeira et al. (2022), Dong et al. (2023), Z. Li et al. (2023), T. T. N. Nguyen et al. (2020), Yeoh et al. (2026), and related route studies. NR fields and noncomparable denominators are retained in Supplementary Tables S1–S2.

Thermal routes are most compelling when they perform more than one function—metal recovery, nitride destruction, fluoride control, or preparation of a qualified mineral product. Their assessment must include the capture of volatile contaminants and the fate of spent salts or additives.

7. HYDROMETALLURGICAL TREATMENT AND RECOVERY OF ALUMINUM COMPOUNDS

7.1 Water leaching

Water leaching dissolves NaCl and KCl, reduces chloride contamination, and simultaneously initiates AlN hydrolysis. Its apparent simplicity masks coupled kinetics: salt dissolution may be rapid, whereas nitride conversion and washing of porous agglomerates may require longer residence or intensified mixing. Optimized water leaching should minimize liquid-to-solid ratio, use staged countercurrent contact, and separate coarse metal before wetting (K. Hu et al., 2021; Jiang & Lee, 2024; Teixeira et al., 2022).

7.2 Acid leaching

Acid leaching can dissolve aluminum-bearing phases and produce sulfate-, chloride-, or nitrate-containing solutions, but co-dissolution of Fe, Mg, Ca, and other impurities increases the demand for purification. Silica can form gels that impair filtration, and residual metal can consume acid while releasing hydrogen. Comparative work on acid and alkaline extraction confirms that lixiviant choice must be linked to feed mineralogy and the target product, rather than to extraction alone (H. Feng et al., 2020; Jiménez et al., 2022; Srivastava & Meshram, 2024).

7.3 Alkaline leaching

NaOH leaching converts reactive aluminum phases to sodium aluminate and can leave many iron-bearing phases in the residue. It is compatible with precipitation of $Al(OH)_3$ and calcination to alumina, but silica, fluoride, and dissolved organic or fine-colloidal

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matter can compromise liquor quality. The removal of silicate using polyacrylamide and targeted defluorination illustrates the need for dedicated purification before precipitation (Gao et al., 2021; T. T. N. Nguyen & Lee, 2021; Türk et al., 2020).

7.4 Selective precipitation and alumina production

Purified aluminum solutions can yield $Al(OH)_3$, gibbsite, boehmite, pseudo-boehmite, alumina, alum, or other salts. Product value depends on phase purity, whiteness, surface area, particle-size distribution, residual Na/Cl/F, and thermal history. Processes producing high-whiteness hydroxide, ultrafine gibbsite, α-alumina, or pure alumina demonstrate the range of possibilities, but each requires control of impurity migration from feed to liquor and product (C.-L. Chen et al., 2025; H. Lv et al., 2022a; Mayani et al., 2025; A. Meshram et al., 2020; T. T. N. Nguyen et al., 2020; M. Shi et al., 2023; Türk et al., 2020).

7.5 Advanced purification operations

Solvent extraction, ion exchange, membranes, and selective crystallization may be justified when a high-value product requires low levels of Fe, Mg, Si, Cu, Zn, or fluoride. Their use should be limited by a clear impurity specification and a recycle plan because adding a polishing step can increase chemical consumption and create secondary regenerant streams. In many dross liquors, precipitation, filtration, and controlled carbonation may be more robust than complex separations.

7.6 Water and reagent recycling

The viability of hydrometallurgy depends on closing water and reagent loops. Recycled wash water reduces freshwater demand but accumulates chloride, fluoride, Na, K, Mg, Ca, and suspended fines. Recycled caustic or acid can reduce OPEX while increasing impurity loading and corrosion. Multi-cycle operation should therefore define a purge strategy, reagent make-up, impurity limits, and the fate of purge brines or precipitates. Waste-liquid recirculation studies are especially relevant because they treat the recycle stream as a kinetic and chemical variable rather than a simple utility (K. Lin et al., 2025).

Table 6 compares aqueous routes using selectivity, recycle, and secondary-residue criteria.

Table 6. Quantitative aqueous-treatment evidence and unresolved scale-up requirements

Route/study	Feed and operating conditions	Reported result	Product/outlet	Unresolved requirement	Class
Water washing (Teixeira et al., 2022)	<2.8 mm; 30 wt% solids; 90 min; ~25 °C	>92% chloride removal	Brine + washed solid	Countercurrent water balance, brine purification, repeated crystallization	D
AlN hydrolysis (Dong et al., 2023)	95 °C; 11.2 h; L/S 7.8 mL/g; 400 rpm	92.45% hydrolysis; Ea 40.24 kJ/mol	NH_3-bearing gas + hydroxylated solid	Peak gas rate, heat release, continuous operation	D
Catalytic hydrolysis (Z. Li et al., 2023)	96.6 °C; 2.85 h; L/S 9.28 mL/g; 12.62 wt% catalyst	99.03% nitride and 81.93% fluoride removal	Detoxified solid + N/F-bearing streams	Catalyst recycle, F outlet, absorber duty	D
NaOH leach/alumina–spinel (T. T. N. Nguyen et al., 2020)	Black dross; alkaline leach, purification, precipitation/calcination	34% whole-process alumina recovery; 99.99% spinel purity reported	Alumina and $MgAl_2O_4$	Global Al balance, caustic recycle, impurity purge, product market	D
Multistage acid leach TEA (Yeoh et al., 2026)	94 kg/batch model; 1–3 leach stages	Yield 21.34–49.93%; Al in product 95.57–96.87%	Modeled alumina	MSP remains highly sensitive to yield/batches; residue contains >50% Al	E

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Route/study	Feed and operating conditions	Reported result	Product/outlet	Unresolved requirement	Class
Roasting–leach / Bayer integration	Thermal activation followed by aqueous recovery	High conversions reported in individual studies; definitions differ	Aluminate/sulfate intermediate or alumina	Reagent recovery, volatile Cl/F, added solids, heat integration	D

Note. Developed by the author based on F. Chen et al., 2024; Deng et al., 2024; H. Feng et al., 2020; Gao et al., 2021; He et al., 2021; K. Huang et al., 2025; Jiménez et al., 2022; Lei et al., 2022; K. Lin et al., 2025; H. Lv et al., 2022a; H. Lv et al., 2022b; Mayani et al., 2025; T. T. N. Nguyen & Lee, 2021; T. T. N. Nguyen et al., 2020; M. Shi et al., 2023; Srivastava & Meshram, 2024; J. Tang et al., 2022a; J. Tang et al., 2022b; Türk et al., 2020; Wajima, 2020; M. Xie et al., 2023a).

No aqueous route should be selected by extraction alone. Saleable-product yield must be divided by the full burden of water, reagents, gas treatment, evaporation, filtration, purge treatment, and residual solids.

Figure 3 compares water, acid, alkaline, roasting–leaching, and Bayer-integrated pathways and identifies water, reagent, mother-liquor, gas, and residue outlets.

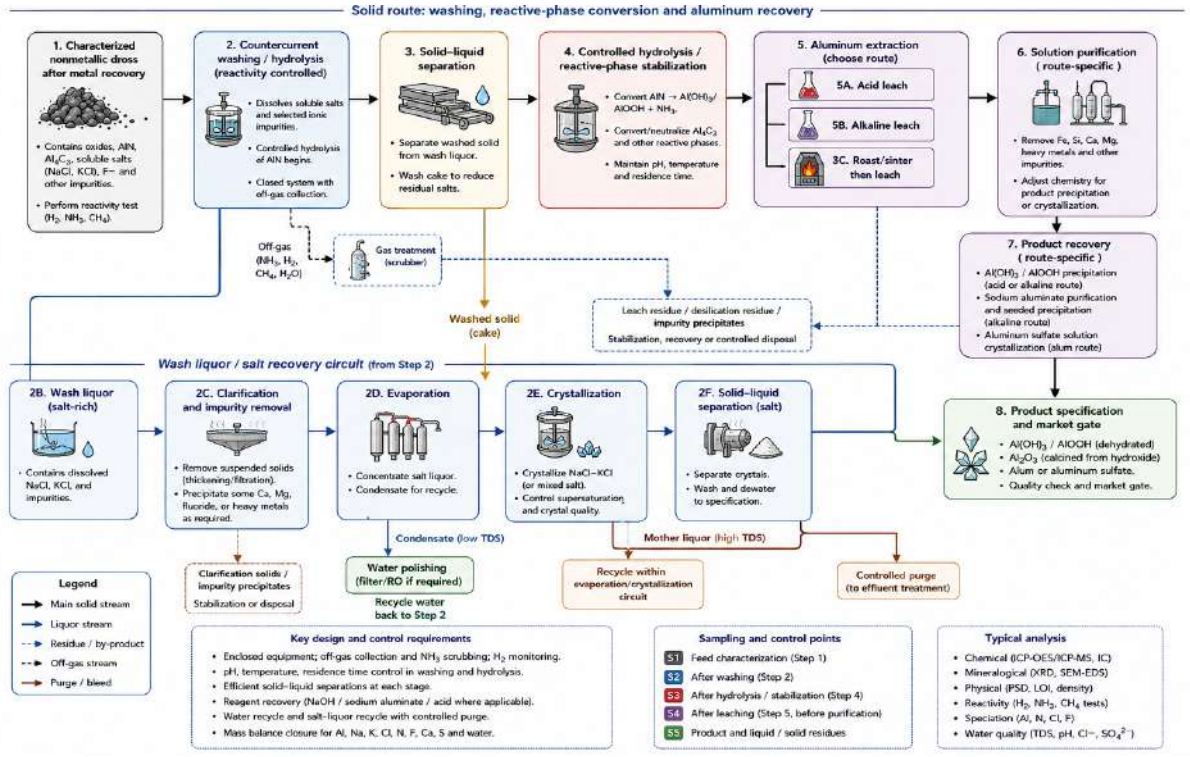

Figure 3. Hydrometallurgical pathways for salt recovery and aluminum-compound production

Note. Developed by the author based on F. Chen et al. (2024), He et al. (2021), K. Lin et al. (2025), T. T. N. Nguyen et al. (2020), M. Shi et al. (2023), and J. Tang et al. (2022a, 2022b).

Gas handling is located at the first wet-contact stage, and the purge points for chloride, fluoride, silica, and dissolved impurities are explicit. Recycle is not treated as indefinite retention.

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8. SALT RECOVERY, NITROGEN VALORIZATION, AND GAS MANAGEMENT

8.1 Dissolution of NaCl and KCl

Salt dissolution is usually rapid, but recovery from porous dross depends on wetting, particle size, agitation, temperature, and the displacement of concentrated pore liquor. High liquid-to-solid ratios improve washing at the expense of evaporation duty. A better design uses multiple stages, countercurrent flow, efficient thickening or filtration, and a final wash targeted to product chloride specification (Hegedüs et al., 2023; K. Hu et al., 2021; Teixeira et al., 2022).

8.2 Crystallization and salt reuse

Evaporation and cooling crystallization can return NaCl–KCl mixtures to the furnace. Salt reuse is credible only when crystal moisture, insoluble solids, fluoride, sulfate, Ca, Mg, and other impurities remain within furnace limits. Hot-treated residue and supergravity studies indicate that salt recovery can be coupled with metal recovery, but long-term quality requires impurity rejection and a purge (Hegedüs et al., 2023; Z. Wang et al., 2023b).

8.3 Impurity accumulation in recycled salts

Each recycle concentrates species that do not leave with the product or purge. Ca and Mg may alter melting behavior; fluoride changes flux chemistry and environmental risk; sulfate and oxide fines reduce effective salt purity; and entrained aluminum compounds can increase dross generation in the next cycle. Multi-cycle salt tests should measure melting point, viscosity or fluidity, metal recovery, corrosion, and slag composition, not only crystal yield.

8.4 Controlled AlN hydrolysis

AlN conversion should be designed as a gas-generating reactor operation. Temperature, pH, solids concentration, particle size, agitation, residence time, and gas stripping determine the rate. Self-driven hydrolysis, catalytic hydrolysis, wet-milling assistance, ultrasound, and recirculated liquor offer different intensification mechanisms (Dong et al., 2023; H. Feng & Jin, 2026; Guo et al., 2023; Jiang & Lee, 2024; Z. (Li et al., 2023; K. Lin et al., 2025; Luo et al., 2025; H. Lv et al., 2020; H.-L. Yang et al., 2022; Y. Zhang et al., 2023). The preferred condition is not necessarily the fastest; it is the condition that produces a stable feed rate to the absorber without local overheating or pressure excursions.

8.5 Ammonia capture and valorization

Ammonia can be absorbed in sulfuric acid to produce ammonium sulfate, in nitric acid to produce ammonium nitrate solution, or in water to produce an ammonia solution. Product selection depends on gas purity, local reagent cost, fertilizer regulation, and the presence of hydrogen or aerosols. Capture efficiency, acid consumption, product concentration, and contaminant transfer must be included in the nitrogen balance. Venting ammonia after “nitrogen removal” is detoxification without value recovery.

8.6 Hydrogen management

Hydrogen can be diluted and safely vented, oxidized in a controlled system, or recovered as fuel when flow and purity justify it. The coexistence of NH_3 and H_2 complicates direct use because the gas may also contain air, moisture, and dust. Continuous measurements of H_2, O_2, NH_3, temperature, and pressure are required, along with flame arrest, compatible materials, and emergency relief. Concepts that couple dross conversion with hydrogen production are promising but require integrated gas purification and safety validation (Lawrence et al., 2025).

Table 7 treats salt, nitrogen, and gas management as co-products of one integrated wet-processing system.

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Table 7. Quantitative design basis for salt, ammonia, and hydrogen management

Operation / stream	Quantitative basis	Product or controlled outlet	Critical control	Readiness	Evidence
Salt dissolution	>92% Cl removal at <2.8 mm, 30 wt% solids, 90 min, ~25 °C	Concentrated NaCl–KCl brine	L/S ratio, entrained fines, countercurrent staging	Laboratory evidence; unit operations mature	Teixeira et al. (2022), D
Crystallization / salt return	Recovery depends on evaporation and impurity purge; multi-cycle data scarce	Dry salt meeting furnace specification	Na/K ratio, moisture, insolubles, Ca, Mg, F, sulfate	Partial industrial relevance; recycle stability underreported	Hegedüs et al. (2023), D
AlN hydrolysis	1 kg AlN → 0.415 kg NH_3 = 0.597 m^3 at 25 °C	NH_3-rich gas and detoxified solid	Measured peak rate, heat removal, pH, solids, residence time	Laboratory dominated	Dong et al. (2023); Z. Li et al. (2023), D
NH_3 absorption	Stoichiometric acid demand set by NH_3 inventory; excess capacity set by peak rate	Ammonium sulfate/nitrate or controlled ammoniacal liquor	pH, NH_4^+, mist, product impurities, absorber redundancy	Integrated recovery not demonstrated at Class A–C	Conceptual integration
Metallic-Al reaction	1 kg Al → 0.112 kg H_2 = 1.360 m^3 at 25 °C	H_2-safe vent or conditioned recovery	H_2/O_2, ignition control, pressure relief, air ingress	Recovery proof of concept; safety basis site-specific	Lawrence et al. (2025), D
Purge management	No closed loop is credible without impurity outlet	Treated purge, precipitate, or controlled disposal	Cl, F, Ca, Mg, sulfate, fines and water closure	Major industrial gap	Evidence map, S1

Note. Developed by the author from stoichiometric calculations and Dong et al. (2023), Z. Li et al. (2023), Teixeira et al. (2022), Hegedüs et al. (2023), and Lawrence et al. (2025).

A salt loop remains open in environmental terms until accumulating impurities have a quantified purge and destination. Nitrogen recovery is circular only when captured product quality and market or internal use are demonstrated.

Figure 4 presents the integrated wet-contact system: metered feed, hydrolysis reactor, gas disengagement, NH_3 absorption, H_2-safe handling, solid–liquid separation, brine crystallization, recycle, and purge.

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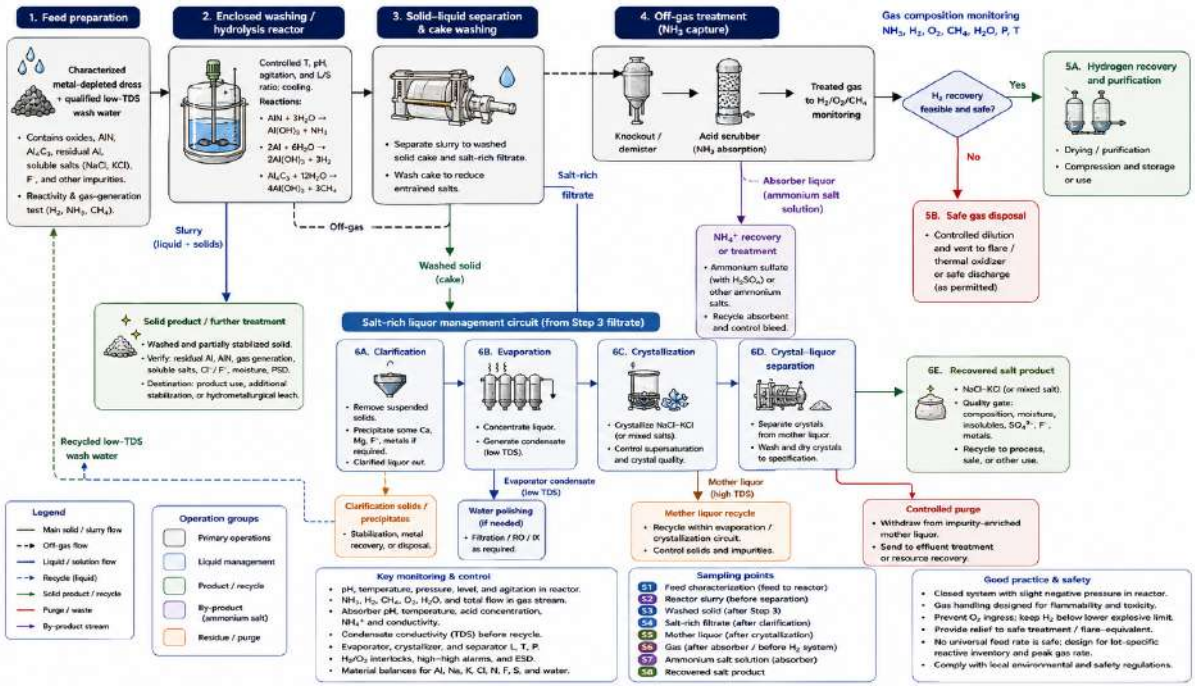

Figure 4. Integration of salt washing, AlN hydrolysis, ammonia capture, and hydrogen management

Note. Developed by the author based on Dong et al. (2023), Z. Li et al. (2023), K. Lin et al. (2025), Teixeira et al. (2022), and Lawrence et al. (2025).

Independent control loops are required for feed rate, temperature, pressure, NH_3 loading, H_2/O_2, brine composition, and purge rate. Gas and brine circuits are therefore core process units rather than end-of-pipe additions.

9. PRODUCTION OF ALUMINA, CERAMICS, CEMENTITIOUS MATERIALS, AND OTHER PRODUCTS

9.1 Alumina and aluminum hydroxides

Alumina and hydroxide routes offer higher value than bulk disposal when feed impurities can be removed economically. Activated alumina, porous alumina, high-whiteness hydroxide, ultrafine gibbsite, α-alumina, and pure alumina have been prepared from dross-derived intermediates (C.-L. Chen et al., 2025; H. Feng & Jin, 2026; H. Lv et al., 2022a; Mayani et al., 2025; T. T. N. Nguyen et al., 2020; M. Shi et al., 2023; Türk et al., 2020). Industrial qualification requires phase composition, loss-on-ignition, Na, Cl, F, Fe, Si, Mg, surface area, particle size, whiteness, and application-specific performance.

9.2 Refractories and ceramics

The Al_2O_3–MgO content of washed or purified dross can support $MgAl_2O_4$ spinel, periclase–spinel refractory, alumina–spinel ceramics, porous ceramics, mullite-containing ceramics, and heat-storage spheres (Benkhelif & Kolli, 2022; H. Feng et al., 2024; H. Feng et al., 2023; W. Li et al., 2022; M. Shi et al., 2022; C. Wang et al., 2026; Zawrah et al., 2022; Y. Zhang et al., 2024). These routes benefit from the use of mineral fractions that are difficult to leach, but residual salt and fluoride can affect sintering, corrosion, and high-temperature stability. The value proposition depends on replacing a defined raw material, not simply incorporating waste.

9.3 Calcium aluminate, cement, and clinker applications

Dross can contribute alumina to premelted calcium aluminate slag, sulfoaluminate–spinel cement, and cement matrices (Gollapalli et al., 2025; S. Hu et al., 2021; Muñoz-Vélez et al., 2023; Ren et al., 2023). The principal risks are gas evolution from metallic Al or AlN, chloride-related durability or reinforcement corrosion, variable setting behavior, and dilution of trace contaminants. Pretreatment must therefore remove reactive metal, nitride, and soluble salts before mix optimization. Mechanical strength alone is insufficient evidence of safe utilization.

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9.4 Geomaterials and alkali-activated products

Recycled salt slag has been investigated in geomaterials and concrete combinations (Elseknidy et al., 2020; Y. Lin et al., 2021; Sun et al., 2024). These applications can consume large tonnage but generally deliver lower unit value than alumina or metal recovery. They should be classified as circular only when the dross substitutes a functional raw material, meets volume-stability and leaching requirements, and does not require excessive dilution. Long-term wet–dry, carbonation, chloride migration, and freeze–thaw behavior may be more important than early compressive strength.

9.5 Adsorbents, zeolites, and metal–organic frameworks

Dross-derived alumina and aluminosilicate phases can be converted into adsorbents for fluoride, phosphate, dyes, aniline, and other contaminants. Reported products include γ-Al_2O_3, porous alumina, layered double hydroxide–zeolite composites, MIL-53(Al), and directly activated dross-derived adsorbents (Lawrence et al., 2025; Mahinroosta & Allahverdi, 2021; Mittal et al., 2024; Yamane et al., 2025; B. Zhu et al., 2024; B. Zhu et al., 2023). Critical evaluation must distinguish capacity in synthetic solutions from performance in real effluent, regeneration, attrition, contaminant release, and the final fate of spent adsorbent.

9.6 Product-quality requirements and market fit

A material-preparation route becomes valorization only when its product meets a defined market specification at a competitive delivered cost. Required evidence includes reproducible composition, physical properties, contaminant limits, batch variability, customer-relevant testing, and a market volume sufficient to generate dross. High-value niche products can improve economics but may absorb only a small fraction of regional residue, whereas construction products can absorb tonnage but risk low-value downcycling.

Table 8 compares product families according to the properties that must be demonstrated before scale-up.

Table 8. Measurable product specifications, test methods, and commercialization barriers

Product family	Minimum measurable specification set	Example test methods	Evidence needed beyond laboratory synthesis	Market-capacity constraint
Alumina/hydroxide	Phase, Al_2O_3 purity, Na, Fe, Si, Cl, F, surface area, PSD, whiteness, loss on ignition	XRD/XRF/ICP; ISO 9277 surface area; ISO 13320 laser diffraction	Lot consistency, impurity control, calcination energy, customer qualification	High-value grades may absorb only a small fraction of regional dross
Recycled NaCl–KCl flux	NaCl/KCl ratio, moisture, insolubles, Ca, Mg, F, sulfate, melting behavior, metal yield	Ion chromatography/ICP; moisture; fusion/remelt trial	At least three recycle cycles without furnace or product-quality drift	Demand bounded by local remelting salt consumption
Spinel / refractory	Phase fraction, density, open porosity, strength, refractoriness, thermal shock, slag corrosion	ASTM C20; ASTM C133; XRD; corrosion cup/rotary test	Pilot firing, dimensional stability, service-corrosion data	Must compete with inexpensive virgin refractory feed
Cementitious/geopolymer	Residual Al/AlN gas release, Cl, expansion, setting, strength, durability, leaching	ASTM C151/C151M; ASTM C109/C109M; EN 196-2; pH-dependent leaching	Long-term expansion, reinforcement compatibility, field exposure	Large market but low value and strict durability liability
Adsorbent / MOF / zeolite	Capacity in real effluent, selectivity, attrition, pressure drop, regeneration, leaching after use	Breakthrough columns; multi-cycle regeneration; particle-strength tests	Real-water validation, spent-media destination, life-cycle comparison	Niche markets cannot consume bulk dross generation

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Product family	Minimum measurable specification set	Example test methods	Evidence needed beyond laboratory synthesis	Market-capacity constraint
Ammonium product	NH_4^+ concentration, free acidity, metals, F, Cl, solids, applicable fertilizer/chemical grade	Ion chromatography/ICP; acidity; solids; jurisdictional product standard	Absorber reliability, contaminant control, offtake agreement	Value depends on purity and regional fertilizer/chemical demand

Note. Developed by the author from the product-quality issues reported by C.-L. Chen et al. (2025), Mayani et al. (2025), M. Shi et al. (2022), Mahinroosta and Allahverdi (2021), Muñoz-Vélez et al. (2023), and Wang et al. (2026). Test standards are examples; contractual acceptance limits remain product- and jurisdiction-specific.

The comparison distinguishes successful synthesis from a qualified product. Market capacity must be compared with regional dross generation so that a high-value niche outlet is not presented as a bulk solution.

10. INTEGRATED PROCESS FLOWSHEETS AND CIRCULAR-PROCESSING STRATEGIES

10.1 Metal-first approach

The default sequence for metal-rich dross is controlled cooling or hot pressing, staged crushing, physical metal recovery, and only then wet treatment of the nonmetallic fraction. This sequence preserves the highest-value component, reduces hydrogen generation, lowers reagent consumption, and prevents aluminum from being converted into a lower-value hydroxide. It is especially appropriate for white dross and coarse black-dross fractions (Kudyba et al., 2021; Lan et al., 2026; Z. Wang et al., 2023a; Z. Wang et al., 2023b; Xue et al., 2022).

10.2 Salt-first approach

A salt-first route is appropriate when soluble salt dominates the residue and interferes with downstream thermal or product-forming steps. Early washing reduces corrosion and chloride contamination, but it must still manage concurrent AlN and metal reactions. The route is credible when brine is sufficiently concentrated for economical crystallization and when recovered salt can be reused over multiple cycles (Hegedüs et al., 2023; K. Hu et al., 2021; Teixeira et al., 2022).

10.3 Nitride-management-first approach

When AlN content and ammonia release dominate the risk, the first controlled operation after metal removal should be hydrolysis in a closed, cooled reactor with gas absorption. Intensification may reduce residence time, but the selected method must remain compatible with salt recovery and solid–liquid separation. A nitride-first design is particularly relevant for fine fractions whose storage and transport are unstable (Dong et al., 2023; Guo et al., 2023; Jiang & Lee, 2024; Z. Li et al., 2023; K. Lin et al., 2025; Luo et al., 2025; H. Lv et al., 2020; H.-L. Yang et al., 2022; Y. Zhang et al., 2023).

10.4 Alumina-product approach

An alumina route combines washing, optional thermal activation, acid or alkaline extraction, solution purification, precipitation, and calcination. It is most suitable for dross with high recoverable nonmetallic Al and a manageable impurity burden. The flowsheet should be designed backward from product specifications: the required alumina phase and purity determine purification, which in turn determines lixiviant and pretreatment selection (C.-L. Chen et al., 2025; F. Chen et al., 2024; Deng et al., 2024; He et al., 2021; K. Huang et al., 2025; H. Lv et al., 2022a; Mayani et al., 2025; T. T. N. Nguyen et al., 2020; M. Shi et al., 2023; Türk et al., 2020).

10.5 Construction-material approach

Construction use should be considered only after metallic Al, AlN, and soluble salts have been reduced to product-specific acceptance limits. Washed residue can then replace alumina-, silica-, or calcium-bearing raw materials. The route must include tests for volume stability, durability, chloride, leaching, and aging. Direct addition of untreated dross is a high-risk dilution method because gas-generating phases can remain active after placement (Elseknidy et al., 2020; Y. Lin et al., 2021; Muñoz-Vélez et al., 2023; Ren et al., 2023; Sun et al., 2024).

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10.6 Zero- or low-waste flowsheets

A low-waste system recovers metal, reusable salts, nitrogen product, process water, and a mineral product while maintaining a small, controlled purge for non-recyclable impurities. "Zero waste" should not mean that all material is forced into a product regardless of quality. A more defensible criterion is that each outlet has a stable composition, defined destination, and verified environmental behavior, with no uncontrolled gas or saline discharge (Y. Liu et al., 2026; D. Wang et al., 2023; Q. Wu et al., 2025; Xiao et al., 2023; X. Zhu & Jin, 2021; X. Zhu et al., 2020).

10.7 Process-selection matrix

Route selection starts with four key variables—metallic Al, soluble salt, AlN, and phase-resolved nonmetallic Al—and then considers particle size, F, local energy, water costs, existing infrastructure, markets, and disposal rules. The optimal route varies by site: a smelter with rotary furnace and salt crystallizer differs from a standalone residue processor near cement or refractory markets.

Table 9 translates feed properties and site constraints into a preferred initial process sequence.

Table 9. Composition-dependent screening calculations and conditional route selection

Measured property	Quantitative screening calculation	Route implication	Required confirmation	Universal threshold?
Metallic Al	Each 1 wt% in feed = 10 kg Al/t and, if reacted, up to 13.60 m^3 H_2/t	Metal-first when net recovered-metal value is positive and H_2 reduction is material	Size-by-assay liberation, recovery cost, oxidation loss, reactive-Al test	No; economic and safety gate is site-specific
AlN	Each 1 wt% in feed = 10 kg AlN/t and up to 4.15 kg or 5.97 m^3 NH_3/t	Dedicated closed hydrolysis or thermal conversion when gas inventory/rate exceeds site acceptance	Direct AlN assay, induction time, peak NH_3 rate, heat release	No; based on absorber/relief capacity and exposure control
Soluble NaCl–KCl	Salt mass sets brine concentration; wash-water excess sets evaporation duty	Salt-first or early wash when salts compromise products and crystallization infrastructure exists	Solubility, L/S optimization, impurity buildup, ≥3 recycle cycles	No; depends on heat, water, and salt offtake
Fluoride	Total F must be closed among solid, liquor, dust, gas, condensate, and purge	Select route that meets product/off-gas limits without uncontrolled transfer	Speciation, volatility/leaching tests, product limit, purge treatment	No cross-product limit
Fine fraction / PSD	Mass below selected cut controls dust, filtration, and reaction-rate inventory	Separate and test fines; avoid assuming bulk behavior	Size-resolved Al^0, AlN, salt, gas evolution, filtration	No universal cut size
Alumina/spinel phases	Extractable Al and refractory spinel determine hydrometallurgical versus ceramic value	Leach/purify only if saleable yield exceeds reagent and residue burden; otherwise product route	Phase-specific extraction, impurity distribution, customer specification	No; mineralogy and market specific

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Measured property	Quantitative screening calculation	Route implication	Required confirmation	Universal threshold?
Product market	Annual qualified-product demand ÷ annual dross-derived output	Reject or cap routes whose market cannot absorb output	Offtake test, price sensitivity, substitute performance	Project-specific
Utilities/regulation	Net water, evaporation, energy, disposal, and compliance costs	May reverse the preferred sequence even for similar feed	Site-specific TEA/LCA and regulatory classification	Jurisdiction-specific

Note. Developed by the author. The calculations are stoichiometric or project-screening relations, not regulatory limits. No universal feed-composition threshold was supported by the heterogeneous corpus.

The matrix replaces arbitrary universal wt% cutoffs with auditable economic, gas-inventory, recycle, product, and regulatory gates. This is the principal exception to the general metal-first recommendation: low recoverable metal content or a dominant salt/AlN risk can justify a different front-end sequence.

Figure 5 presents the integrated value-recovery flowsheet and the minimum balance-control points for Al, Cl, N, F, Na, K, water, dust, products, and purges.

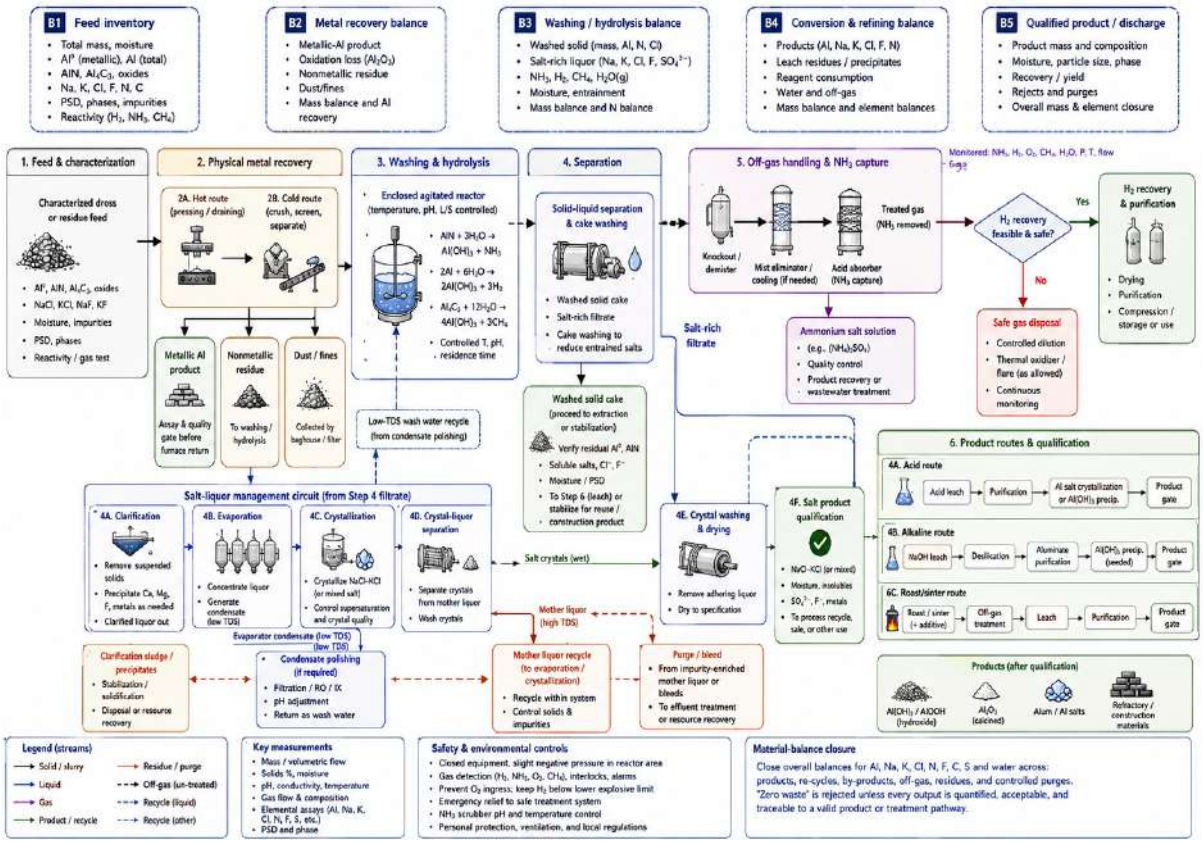

Figure 5. Integrated value-recovery flowsheet and mandatory material-balance control points

Note. Developed by the author based on Hegedüs et al. (2023), Kudyba et al. (2021), K. Lin et al. (2025), T. T. N. Nguyen et al. (2020), Teixeira et al. (2022), and Z. Wang et al. (2023a, 2023b).

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The control points convert "zero waste" into an auditable claim. A route fails the closure test when any relevant element, water, dust, or purge lacks a measured outlet.

11. SUSTAINABILITY, LIFE-CYCLE PERFORMANCE, AND TECHNO-ECONOMIC ASSESSMENT

11.1 Functional unit and system boundaries

Meaningful comparison requires both a waste-management functional unit (1 t of dross treated) and a product functional unit (for example, 1 t of recovered Al or 1 t of qualified alumina). One tonne of landfill avoided can overreward dilution or low-quality incorporation. Boundaries must include front-end metal recovery, water and reagent production, evaporation, drying, calcination, gas treatment, purge disposal, transport, and substitution credits.

11.2 Mass-balance indicators

At a minimum, the process should reconcile the total mass with the elements Al, Cl, N, F, Na, K, Mg, and water. Separate indicators are needed for metallic-Al recovery, nonmetallic-Al recovery, salt recovery, nitrogen capture, product yield, landfill fraction, and losses to gas, liquor, dust, or purge. Reporting only "Al recovery" can double-count metal remelting and aluminum-compound production or ignore aluminum retained in residues.

11.3 Energy indicators

Energy demand includes hot-dross handling, crushing, grinding, pumping, evaporation, drying, calcination, and gas treatment. Evaporation can dominate salt recovery when wash water is excessive, while calcination dominates many alumina routes. Credits for avoided primary aluminum or virgin raw material should be applied only to the quantity and quality actually displaced. Exergoeconomic analysis can reveal where high-quality energy is consumed for low-value separations (P. Zhang et al., 2023).

11.4 Water footprint

Water performance should be reported as gross use, net make-up, recycle ratio, purge volume, and water leaving with wet solids or products. A route with high internal recycle can still require substantial evaporation or suffer impurity accumulation. Water-scarce sites may favor dry recovery and concentrated countercurrent washing, while sites with low-cost waste heat may allow higher evaporation rates. The water and energy balances are therefore coupled.

11.5 Carbon footprint

The dominant credit often comes from metallic Al that actually displaces primary or secondary metal of equivalent quality. Thermal activation, evaporation, calcination, and reagent production can reverse rankings under carbon-intensive energy. The LCA studies in the corpus use different functional units, locations, substitution credits, and system boundaries; their numerical rankings are therefore not transferable without harmonization (Vallejo-Olivares et al., 2024; Xiao et al., 2023; X. Zhu & Jin, 2021; X. Zhu et al., 2020).

11.6 Techno-economic analysis

TEA must report scale, currency year, batch or continuous basis, uptime, CAPEX, fixed and variable OPEX, product yield and acceptance, disposal credit, and sensitivity. Yeoh et al. (2026) modeled 94 kg/batch and reported alumina yields of 21.34%, 37.49%, and 49.93% for one-, two-, and three-stage leaching; the two-stage case had the lowest modeled minimum selling price, 165.59 USD/kg, while yield and annual batch number dominated sensitivity. The very high modeled selling price and residual solids containing more than 50% Al demonstrate that simulated scale-up is not equivalent to commercial readiness.

11.7 Circularity and avoided burden

Circularity is credited only for equivalent functional substitution and controlled loops. Reusable salt returned to the furnace is closed loop; qualified alumina replacing a commercial feed is substitution; low-grade incorporation without equivalent performance is downcycling; and immobilization without resource recovery is stabilization. Multi-cycle salt quality, purge treatment, product acceptance, and market capacity determine which category applies.

Table 10 harmonizes the LCA and TEA studies sufficiently to show why their rankings cannot be compared without re-modeling common boundaries.

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Table 10. Harmonized comparison of LCA, exergoeconomic, and techno-economic evidence

Study/route	Functional unit and boundary	Scale/location	Key reported finding	Critical comparability limitation
X. Zhu et al. (2020), alumina recovery	Alumina-route comparison with bauxite benchmark	Modeled Chinese system	Normalized midpoint impact 32.16% lower; reported cost 130.01 USD/t alumina; ammonium-sulfate credit 22.18 USD	Substitution credit, energy mix, and process assumptions drive result
X. Zhu & Jin (2021), three emerging routes	Life-cycle comparison of Chinese recovery alternatives	Modeled / emerging	Route ranking depended on process energy, reagent, and recovered-product credits	No common industrial operating dataset
Xiao et al. (2023), hybrid LCA pathways	Pathway identification for secondary dross	Chinese hybrid LCA	Acid polyaluminum-chloride pathway performed worst in most assessed categories	Functional products and credits differ among scenarios
P. Zhang et al. (2023), alumina process	Exergoeconomic and exergoenvironmental analysis	Modeled Chinese process	Identified energy and cost improvement targets	Model performance is not pilot operability
Vallejo-Olivares et al. (2024), rotary-furnace recycling	Recycling of ash, dross, and shavings plus salt-slag valorization	Industrial-context LCA	Benefits depend on metal recovery, salt-slag valorization, and avoided burdens	Mixed feed and regional energy/transport reduce transferability
Yeoh et al. (2026), acid leach–precipitation	94 kg/batch Aspen model and discounted cash flow	Malaysia / modeled scale-up	Yield 21.34–49.93%; lowest MSP 165.59 USD/kg; yield and batches/year dominate sensitivity	Small batch, high MSP, model assumptions, Al-rich residue
Required harmonized case	1 t dross plus product-normalized results; cradle-to-gate with common credits	Site-specific	Report Al, salt, N, water, purge, energy, CAPEX/OPEX, market acceptance and uncertainty	Only then can route rankings be compared

Note. Developed by the author based on X. Zhu et al. (2020), X. Zhu and Jin (2021), Xiao et al. (2023), P. Zhang et al. (2023), Vallejo-Olivares et al. (2024), and Yeoh et al. (2026). Monetary results are reproduced in the units reported by the source studies and are not normalized to a common price year.

The table shows that no route can be labeled “most sustainable” across the corpus. A common model must vary metal credit, energy mix, transport, evaporation duty, product acceptance, disposal cost, and recycling lifetime.

12. INDUSTRIAL READINESS, FAILURE MODES, AND RESEARCH AGENDA

12.1 Technology-readiness classification

Readiness was assigned route by route from the coded corpus. Mature unit operations such as crushing, screening, hot pressing, filtration, and crystallization do not automatically make an integrated dross flowsheet mature. The least-demonstrated linked step—often gas capture, recycle stability, product acceptance, or purge treatment—sets the readiness of the complete route.

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12.2 Principal failure modes

Common failures arise from insufficient liberation, uncontrolled AlN hydrolysis, residual metallic Al, dilute wash circuits, impurity buildup in recycled salt, silica gel formation, off-spec alumina, and incomplete balances. These failures are connected: overgrinding can improve leaching while worsening filtration; more washing can reduce chloride while increasing evaporation; faster hydrolysis can reduce reactor volume while exceeding absorber capacity. Integrated design must therefore optimize the bottleneck system, not each unit operation independently.

12.3 Critical research gaps

The most important gaps are standardized sampling; rapid, direct assays for metallic Al and AlN; size-resolved phase characterization; complete Al–Cl–N–F–water balances; simultaneous NH_3 and H_2 measurement; multi-cycle salt recovery; long-term aging and leaching of products; representative continuous or pilot operation; and linked LCA–TEA under regional utility and market conditions. Reviews published across the period consistently identify the distance between laboratory valorization and integrated industrial evidence (Harmaji et al., 2024; K. Huang & Yi, 2023; Y. Liu et al., 2026; Modalavalasa & Ayyagari, 2024; D. Wang et al., 2023; R. Wang et al., 2026; Q. Wu et al., 2025; X. Wu et al., 2025; J. Yang et al., 2024; Yuan et al., 2023).

12.4 Research agenda

Priority research should develop: (1) certified methods for metallic Al and AlN; (2) modular hydrolysis–absorption systems with dynamic gas-rate control; (3) countercurrent washing with low net water use; (4) selective salt crystallization and impurity purging over many cycles; (5) heat integration between hot dross, evaporation, drying, and calcination; (6) product qualification protocols for alumina, refractories, adsorbents, and construction materials; (7) pilot campaigns with reconciled balances; and (8) digital models that connect feed variability to route selection and control limits.

12.5 Integrated decision framework

The proposed framework starts with feed origin and representative sampling, then quantifies metallic Al, salt, AlN, mineral phases, F, and particle size. It chooses a metal-first, salt-first, or nitrides-first front end. The downstream product route is selected after safety and recycle criteria are met. Each flowsheet is screened through product specs, mass and energy balance, life-cycle burden, economics, and evidence class. Routes failing gas, purge, market, or stability criteria are redesigns rather than circular.

Table 11 defines the evidence needed to move a dross-treatment concept from laboratory success to commercial readiness.

Table 11. Route-specific industrial readiness supported by the 106-publication corpus

Technology / integrated route	Corpus evidence and current class	Principal industrial bottleneck	Confidence / advancement requirement
Hot dross pressing; crushing/screening	Mature unit operations; corpus support mainly reviews and laboratory route studies	Oxidation/logistics; metal remaining in fines; incomplete global balances	High for unit operations, moderate for route; require reconciled Al balance
Hot extrusion/supergravity	>92–97.14% reported in Class D studies	Hot-feed variability, continuous throughput, equipment durability	Moderate-low; pilot campaign with energy and dust balance
Salt washing + crystallization + salt return	Laboratory washing evidence; industrially familiar unit operations; integrated class A–C evidence scarce	Evaporation duty, fine carryover, impurity buildup, purge, furnace acceptance	Moderate; ≥3 recycle cycles and remelt qualification
AlN hydrolysis + NH_3 capture + H_2 management	Conversion demonstrated primarily in Class D batch studies	Peak gas/heat rate, relief, absorber integration, abnormal operation	Low–moderate; closed pilot reactor and HAZOP evidence

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Technology / integrated route	Corpus evidence and current class	Principal industrial bottleneck	Confidence / advancement requirement
High-purity alumina/hydroxide	Laboratory products and one modeled TEA; no commercial integrated campaign	Purification, reagent recycle, low global yield, energy, market grade	Low–moderate; pilot mass balance and customer qualification
Ceramic/refractory / cement product	Many Class D material studies	Residual Al/AlN/Cl/F, scale firing, durability, market absorption	Moderate for synthesis, low for bulk waste solution; long-term tests
Adsorbent/zeolite / MOF	Mostly laboratory or proof-of-concept products; one pilot adsorbent study	Real-effluent performance, regeneration, attrition, spent-media outlet, market size	Low; continuous column and offtake evidence
Integrated low-waste flowsheet	No Class C integrated study identified	Closure of Al–Cl–N–F–Na–K–water, gas system, product market, purge	Low; demonstration with reconciled balances and harmonized LCA/TEA

Note. Developed by the author from the study-level evidence coding in Supplementary Table S1. Readiness refers to the integrated route, not the familiarity of an individual unit operation.

The route-specific assessment prevents mature generic equipment from masking an immature integrated process. No route advances solely because one component operation is commercial elsewhere.

Table 12 converts the principal scale-up risks into observable symptoms and corrective design actions.

Table 12. Failure modes, diagnosis, and corrective actions

Symptom	Probable cause	Consequence	Corrective action
Low metallic-Al recovery	Insufficient liberation or delayed hot processing	Loss of high-value metal; higher H_2 risk	Optimize cooling, staged breakage, and early metal removal
Excess NH_3 release	Uncontrolled AlN hydrolysis or feed variability	Occupational exposure and absorber overload	Meter feed/water; cool reactor; size absorber to peak rate
Unexpected H_2	Residual metal entering wet alkaline stage	Flammability and pressure excursion	Improve metal-first recovery; continuous H_2/O_2 monitoring
High salt in product	Insufficient washing or pore-liquid displacement	Off-spec alumina/ceramic; corrosion	Countercurrent wash, better filtration, final product wash
Large effluent volume	High liquid-to-solid ratio and weak recycle	High evaporation and treatment cost	High-solids washing, condensate reuse, controlled purge
Recycled-salt deterioration	Accumulation of F, sulfate, Ca/Mg, and fines	Poor furnace performance and more slag	Clarification, selective crystallization, impurity purge
Leach filtration failure	Fine particles or silica gel	Low throughput and product loss	Control grinding, pH, temperature, and flocculation

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Symptom	Probable cause	Consequence	Corrective action
Impure alumina product	Co-extraction of Fe, Mg, Si, Na, Cl, F	Low market value	Purify liquor; redesign precipitation and washing
Expansion in cement/ceramic	Residual Al or AlN; inadequate aging	Cracking and durability loss	Detoxify; verify gas evolution and long-term stability
Unreconciled mass balance	Missing dust, gas, liquor, or purge analyses	Overstated recovery and circularity	Sample every outlet and reconcile elemental balances

Note. Developed by the author from failure mechanisms reported across physical, aqueous, thermal, and product routes. Each corrective action must be converted into an instrumented pilot acceptance test.

The failure matrix defines measurable pilot acceptance tests. Symptoms should be linked to alarms, interlocks, sampling frequency, control limits, and a documented response rather than corrected only after product failure.

Figure 6 integrates feed characterization, conditional front-end sequence, gas-risk control, recycle closure, product qualification, harmonized LCA/TEA, evidence level, and objective go/no-go decisions.

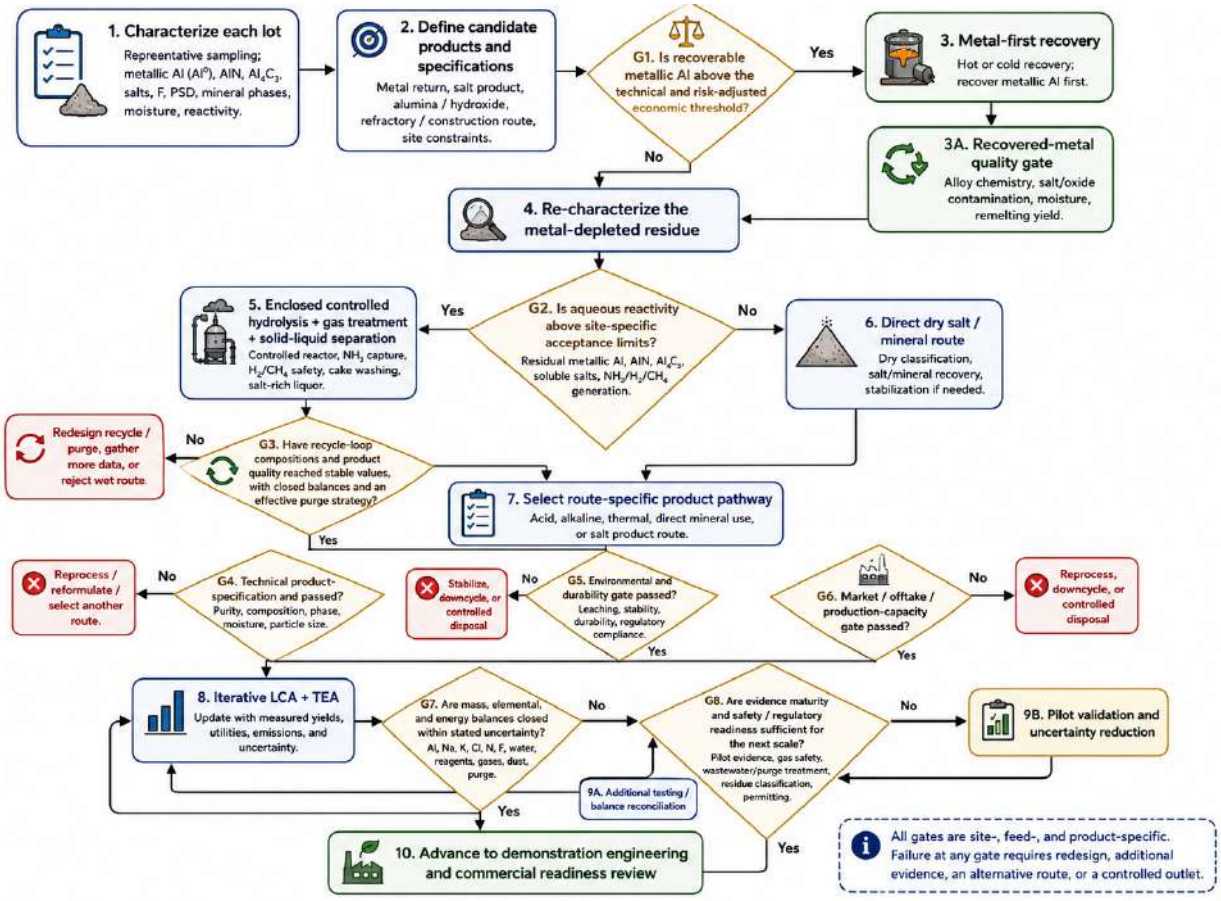

Figure 6. Decision framework with objective go/no-go gates

Note. Developed by the author from the evidence map, quantitative screening calculations, and integrated assessment criteria developed in this review.

A route advances only when it preserves recoverable value, controls NH_3/H_2, closes the salt-and-water loop for repeated cycles, meets product and market gates, identifies every purge, and reaches pilot evidence with reconciled balances.

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13. CONCLUSIONS

Secondary aluminum dross and salt slag must be treated as variable secondary resources whose recoverable value and process hazard arise from the same constituents. Route selection must begin with lot-specific data on metallic Al, AlN, soluble salts, fluorides, mineral phases, and particle size. Metal-first processing is preferred only when recovered-metal value and risk reduction justify the added operation; low-metal, salt-rich, or nitride-rich fines can require salt- or risk-management-first treatment. Water contact must be designed from measured gas-release kinetics and conservative stoichiometric inventories, with closed NH_3 capture, H_2-safe handling, cooling, relief, and abnormal-operation controls. Salt recovery is credible only after repeated recycle demonstrates stable flux quality and a controlled impurity purge. Alumina, refractory, cementitious, and functional products count as valorization only when they meet measurable specifications, durability and leaching requirements, and realistic market capacity. The evidence map shows that laboratory studies dominate and that no continuous integrated Class C campaign was identified. Industrial advancement, therefore, requires pilot or demonstration operations with reconciled Al–Cl–N–F–Na–K–water balances, qualified products, quantified purges, and harmonized LCA and TEA. "Zero waste" is not supported when an element, gas, liquid, dust, or residue lacks an identified and acceptable outlet.

Metal recovery should generally precede intensive wet or thermal conversion because metallic aluminum has the highest direct value and can generate hydrogen or consume reagent if carried into aqueous processing. Controlled cooling, hot pressing or separation, staged comminution, and dry concentration reduce both economic loss and downstream hazard.

Salt washing is sustainable only when the brine is concentrated, clarified, crystallized, and recycled with a defined impurity purge. Excessive dilution transfers the burden to evaporation and creates a saline effluent problem. Water use, condensate recycle, crystal quality, and repeated furnace performance must be demonstrated together.

Aluminum nitride hydrolysis should be operated as a controlled reaction with heat removal, pressure management, continuous monitoring, and ammonia capture. Nitrogen removal without gas recovery may improve safety, but it does not achieve full value recovery. Hydrogen generated from residual metal requires independent monitoring and a safe vent, oxidation, or purification strategy.

Alumina, hydroxide, spinel, refractory, ceramic, adsorbent, and cementitious routes are technically justified only when they use a well-characterized and adequately detoxified feed and deliver products that meet market specifications. Strength, extraction, or adsorption results alone do not establish commercial value, durability, or environmental stability.

The major limitation to industrial adoption is not the absence of conversion chemistry; it is the lack of integrated evidence. Representative sampling, direct metallic-Al and AlN assays, complete Al–Cl–N–F–water balances, multi-cycle salt recovery, gas management, continuous pilot operation, product qualification, and combined life-cycle and techno-economic assessment are the decisive requirements.

A credible circular flowsheet therefore follows a hierarchy: preserve metal, control reactive phases, recover salts and nitrogen where practical, close water and energy loops, qualify the mineral product, and maintain a controlled outlet for accumulating impurities. Sustainability is demonstrated by stable products and reconciled balances, not by landfill diversion or a single high recovery percentage.

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