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Review

Circular Resource Flows and Logistics Networks in Copper Mining: Resource Qualification, Industrial Symbiosis, and Environmental Safety. A Systematic Review

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Abstract

Copper-mining operations generate tailings, process waters, slags, and other residues that may yield recoverable metals, reusable water, and secondary construction materials. Yet recovery at the process boundary does not establish industrial reintegration. This systematic review examines the interfaces among resource qualification, circular logistics, industrial symbiosis, and environmental safety, following PRISMA 2020 reporting guidance. The archived Scopus dataset (S0) contains 478 records. A documented copper-term filter retained 105 records for formal screening (S1); 33 were excluded at title/abstract screening and 11 of the 72 full-text reports assessed were excluded, leaving 61 publications (44 research articles, 14 reviews, and three book chapters). Search and selection were conducted between 8 June and 9 October 2026. Across heterogeneous study designs, the evidence is stronger for resource recovery and material characterization than for recipient-specific qualification, traceable delivery, verified uptake, and residual management. We introduce the Circular Resource Qualification–Logistics Interface (CRQLI), an author-derived conceptual framework that distinguishes recovered, qualified, delivered, and utilized outputs and specifies chemical, logistical, and environmental decision gates. CRQLI has not been operationally validated. Its proposed indicators and testable hypotheses provide a basis for future receiver-linked assessments. Single-reviewer screening, a restrictive thematic filter, and heterogeneous reporting limit the generalizability of the synthesis.

Keywords: copper mining; circular logistics; industrial symbiosis; mine tailings; resource qualification

1. Introduction

Copper underpins electrification, infrastructure, and industrial manufacturing. Its production, however, generates large and chemically heterogeneous streams of tailings, mine-affected water, slags, and processing residues that may require management long after ore extraction. These streams can also contain recoverable metals, reusable water, and mineral constituents capable of substituting for primary inputs. The central question is therefore not merely whether a constituent can be recovered, but whether the resulting output can be qualified, transported, accepted, and used without transferring unacceptable environmental burdens elsewhere [1–4]. The scale of copper-tailings management makes this distinction consequential [5,6].

Substantial progress has been made in understanding what can be recovered. Hydrometallurgical and biological approaches, together with increasingly refined mineralogical and geochemical

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characterization, have expanded the range of potentially accessible metals and recovery pathways [7–12]. Recent reviews synthesize advances in leaching, reprocessing, flotation-based tailings valorization, and the extraction of valuable constituents from mine residues [13–15]. Other contributions address technogenic-resource processing, integrated mineral recovery, and the reduction of mining-related impacts [16–19]. These studies are essential, but they also expose a conceptual boundary: the presence of a valuable element, or even its successful separation, does not establish the quality, destination, or sustained usefulness of the recovered product.

A similar boundary emerges in the valorization of solid residues. Copper tailings and related mineral streams have been investigated as constituents of alkali-activated binders, mortars, concrete, and other engineered materials [20–25]. These applications may reduce reliance on virgin raw materials, but their viability depends on more than mechanical performance at the point of manufacture. Mineralogical variability, contaminant speciation, leaching under relevant exposure conditions, aging, and durability can determine whether a material remains acceptable throughout its service life [26–29]. Broader syntheses of mining-waste applications provide useful context, although proposed uses must not be mistaken for documented industrial demand or verified copper-mine offtake [30–32].

Water recovery makes the limits of a process-centered perspective especially visible. Membranes, dewatering strategies, and integrated treatment systems can increase the quantity of water available for reuse, while also changing energy demand and the composition of concentrated residual streams [1,33–35]. However, water recovered at a treatment outlet is not necessarily water available to a receiving process. Its salinity, dissolved constituents, temporal availability, conveyance requirements, and compatibility with operational demand all affect its practical value. As quantitative work on water circularity under uncertainty indicates, improved recovery cannot be assumed to improve whole-system performance without considering losses and trade-offs across the relevant boundary [36].

These examples reveal an underexamined interface between recovery science and supply-chain design. Mining residues originate at geographically fixed sites, often in variable quantities and compositions; prospective users may be distant, subject to stringent product specifications, or unable to absorb supply at the rate at which it is generated. Storage, segregation, conditioning, transport, traceability, and receiver acceptance can therefore decide whether a recovery pathway becomes a functioning circular exchange. Contributions on reverse logistics, digital integration, and circular-economy strategy in copper mining point toward this wider perspective [37–40]. Prospective life-cycle assessments further demonstrate why a pathway that diverts material from disposal must still be tested for energy use, emissions, reagent demand, and residual burdens before an environmental advantage is claimed [41,42].

The principal research gap lies at the interface between recovery and downstream use. A recoverable constituent is not necessarily a specification-compliant product; a qualified product is not necessarily deliverable at an acceptable cost; and delivery does not establish verified industrial use. Moreover, none of these outcomes alone demonstrates net environmental benefit. Although individual studies address parts of this sequence, their results seldom provide comparable evidence across resource characterization, product qualification, logistics, recipient acceptance, and residual fate [36,42,43].

This systematic review therefore examines the recovery-to-reintegration chain as the unit of analysis for circular resource flows in copper mining. Drawing on 61 distinct publications, it asks: (i) which water, metal, and mineral streams are potentially recoverable, and what compositional constraints govern their qualification; (ii) how processing, storage, transport, and network configuration shape their delivery to compatible recipients; (iii) what evidence distinguishes proposed industrial symbiosis from verified utilization; and (iv) how environmental risk, cost, energy, and residual management should condition claims of circular performance. The review contributes a structured interpretation of the evidence and introduces the Circular Resource Qualification–Logistics Interface (CRQLI), a conceptual architecture that connects chemical and functional qualification with logistics

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decisions and environmental safeguards. Rather than presenting an untested network as an operational solution, the framework specifies the interfaces, evidence requirements, and measurable outcomes through which future research can evaluate whether recovered resources actually complete a safe and useful circular journey.

2. Materials and Methods

This review follows PRISMA 2020 reporting guidance [44] and adopts the recovery-to-reintegration chain as its unit of analysis: generation and characterization; processing and recovery; functional and environmental qualification; inventory, storage and transportation; and recipient acceptance and verified use. From a logistics perspective, these stages create coupled decisions about batch segregation, quality-dependent routing, temporal supply–demand matching, transport feasibility and traceable custody. Recoverability, feasible delivery and industrial utilization are therefore treated as distinct outcomes, not interchangeable indicators of circularity.

The selection pathway was reconciled against Supplementary Tables S0 and S1. The Scopus archive (S0) contains 478 records; a case-insensitive occurrence filter requiring "copper" in the title, abstract or keywords retained 105 for screening and excluded 373 before formal screening. S1 documents 33 title/abstract exclusions, 72 reports retrieved and assessed in full, 11 full-text exclusions and 61 inclusions. The 373 preliminary exclusions were thematic, not duplicate removals. The search expression and limitations concerning the query timestamp and pre-archive deduplication are specified in Section 2.1.

The review question was formulated as follows: How can recovered water, metals, and secondary mineral materials from copper mining be integrated into circular logistics networks and industrial symbiosis arrangements while maintaining environmental safety and credible sustainability performance? Four complementary analytical dimensions were defined a priori for the synthesis: (i) resource availability, composition, recoverability, and product quality; (ii) recovery and processing configurations together with storage, transport, and network requirements; (iii) industrial symbiosis, recipient compatibility, and actual or proposed downstream utilization; and (iv) environmental and economic performance, including contaminant mobility, energy demand, emissions, and residual management.

A single reviewer performed selection during the reported period of 8 June–9 October 2026. The eligible publication window was 2007–2026; the 61 included publications (44 articles, 14 reviews and three book chapters) were published during 2013–2026. All 72 reports advancing from title/abstract screening were retrieved and assessed in full. The exact Scopus execution timestamp and any pre-archive deduplication count are not independently documented.

Eligibility was defined by relevance to copper mining, copper-bearing residues, mine water, or explicitly transferable mining-resource contexts, together with substantive information on at least one link in the recovery-to-reintegration chain. Eligible contributions could be experimental studies, site investigations, prospective or retrospective environmental assessments, techno-economic or decision-support analyses, logistics and circularity models, and relevant reviews. Publications focused exclusively on unrelated sectors without a defensible connection to mining-derived secondary resources were outside scope. Review articles were used to characterize established knowledge and research gaps, not treated as independent replications of primary experimental results.

For synthesis, studies were classified according to their evidentiary relationship to the review question: direct copper-mining evidence; transferable evidence from other mining residues or resource-recovery systems; and contextual evidence concerning circular logistics, industrial symbiosis, or environmental decision-making. This distinction prevents results obtained in dissimilar feedstocks, geographic settings, or operational scales from being presented as demonstrated performance at copper mines. A study could contribute to multiple thematic domains without being counted more than once in the included-study total.

The recorded flow is arithmetically consistent: 478 − 373 = 105 screened; 105 − 33 = 72 full texts assessed; and 72 − 11 = 61 included. S1 contains record-level reasons for 44 exclusions after the

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thematic filter and inclusion rationales for the 61 retained publications. The 373 initial removals were based on indexed keyword occurrence, not full-text eligibility assessment.

All 72 reports advancing beyond title/abstract screening were read in full for eligibility, and the full texts of the 61 included publications informed the qualitative synthesis. The single author conducted screening and interpretive extraction; no independent duplicate extraction, investigator contact to resolve missing data, or automated extraction procedure is documented. The information sought concerned resource origin and feedstock composition, recovery or treatment pathway, reported output quality and performance, possible recipient and use, logistics requirements, environmental safeguards, and reported economic or life-cycle boundaries. Results were retained in their original study-specific units and contexts; no common effect measure, imputed missing value, or pooled estimate was calculated. Supplementary Table S1 documents record-level inclusion and exclusion rationales but is not a complete quantitative extraction workbook. The critical interpretation considered seven claim-level domains where applicable: (i) feedstock representativeness; (ii) analytical characterization and compositional variability; (iii) material and water balances; (iv) functional and environmental product qualification; (v) scale and duration; (vi) life-cycle, cost and logistics boundaries; and (vii) uncertainty and transferability. A domain not applicable to a given study design was not treated as failed evidence, and unreported information was not assumed. This is a design-sensitive narrative appraisal, not a validated study-level risk-of-bias tool, a separately archived rating for each publication, or a formal assessment of certainty of evidence. Table 3 defines evidentiary thresholds for claims rather than ratings assigned to the 61 studies.

A narrative, configurational synthesis was used rather than meta-analysis because studies differed in feedstock, target resource, product specification, outcome definition, scale, and system boundary. Findings were organized by the stages of the recovery-to-reintegration chain and by direct, transferable, or contextual relevance; individual studies could inform more than one domain without being double-counted. Laboratory results were interpreted only under their reported conditions, prospective assessments as conditional scenarios, and reviews or conceptual proposals as contextual synthesis rather than independent operational replications. No statistical effect-size synthesis, subgroup meta-analysis, quantitative sensitivity analysis, or formal assessment of small-study effects or publication bias was undertaken. Potential reporting and selection biases were considered narratively when qualifying claims, but their magnitude was not estimated. Because the evidence was not pooled, the review reports no pooled effects, confidence intervals, or statistical heterogeneity estimates. The synthesis identifies interfaces and testable gaps rather than demonstrating that a proposed network has been operationally validated.

2.1. Steps of the Systematic Review

The question, scope, eligibility logic, and synthesis domains were established to distinguish recoverable-resource potential from demonstrable downstream reintegration. Inclusion was not conditional on a single paper addressing all dimensions; rather, each study was mapped to the stages for which it supplied relevant evidence.

The S0 archive was subjected to the predefined case-insensitive occurrence rule for “copper” in title, abstract or keywords. Of 478 records, 105 met the rule and advanced to S1; 373 did not and were excluded at this preliminary thematic-filter stage. These 373 exclusions are neither duplicate removals nor full-text eligibility decisions. Of the 105 screened records, 33 were excluded on title/abstract grounds; all 72 remaining reports were retrieved and read in full, with 11 excluded after eligibility assessment and 61 retained for synthesis. The explicit copper-term restriction may omit transferable work without that term in indexed fields; this limitation concerns search coverage, not whether the retained reports were read in full.

Figure 1 depicts the selection pathway in PRISMA 2020 terms. The 478 identified records comprise 373 removed before formal screening by the explicitly documented copper-term thematic restriction and 105 screened records. Following 33 title/abstract exclusions, all 72 reports were retrieved and assessed in full text; 11 were excluded and 61 were included. The 373 pre-screening removals

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must not be interpreted as duplicates. The counts are reconcilable against S0–S1, whereas the reported search-and-selection period is 8 June–9 October 2026 and no pre-archive deduplication count is documented.

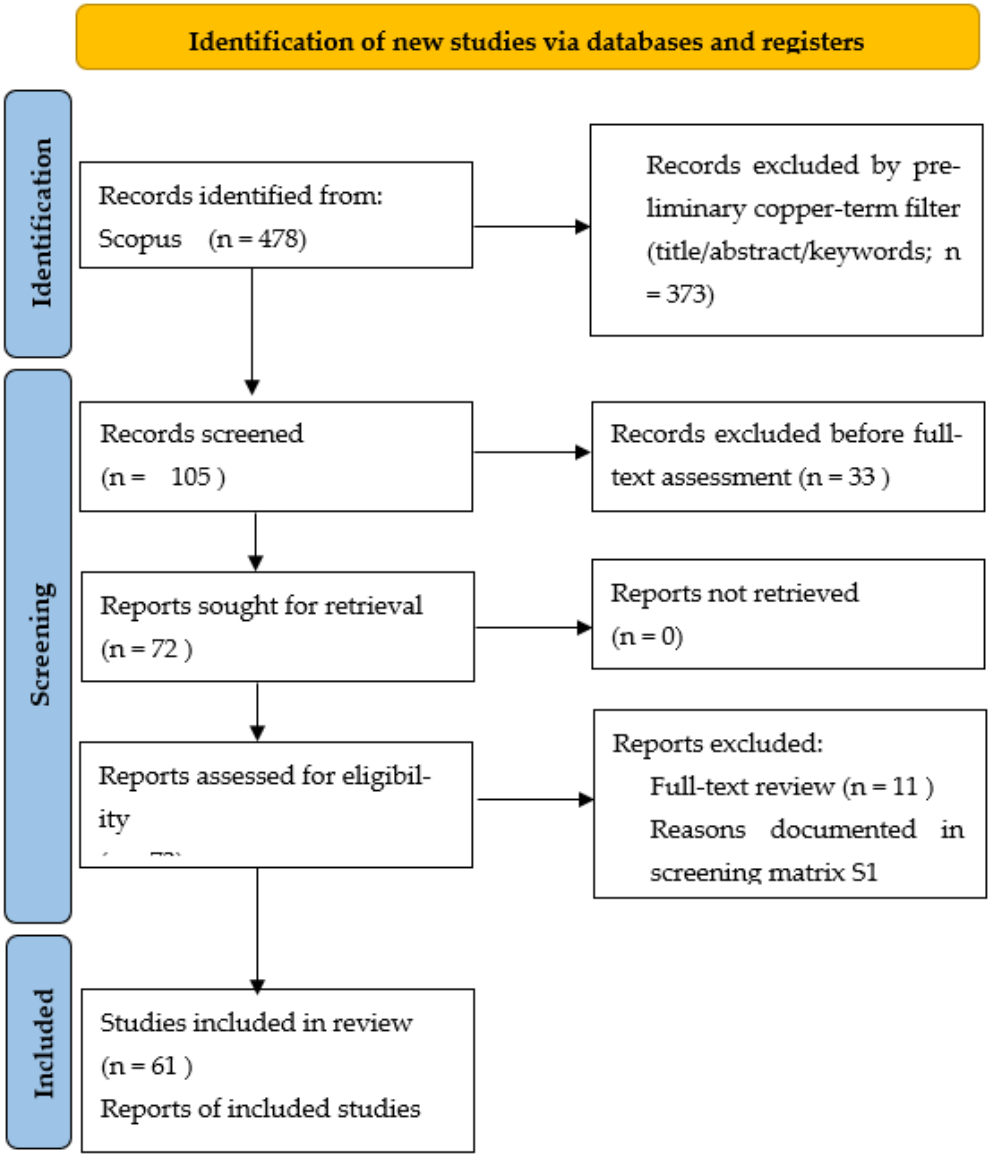


Figure 1. PRISMA 2020 flow diagram of the documented Scopus identification and study-selection pathway (adapted from [44]). S0 comprises 478 records; a preliminary thematic restriction requiring "copper" in title, abstract or keywords excluded 373 records before formal screening and retained 105 in S1. Subsequent screening excluded 33 records by title/abstract; all 72 remaining reports were retrieved and assessed in full text, with 11 excluded and 61 publications included. The 373 preliminary thematic exclusions are not duplicates. The reported search-and-selection period was 8 June–9 October 2026; a pre-archive deduplication count is not documented.

Original Scopus Advanced Search expression, as confirmed by the author (TITLE-ABS-KEY; publication years 2007–2026):
TITLE-ABS-KEY((("copper mining" OR "copper mine" OR "copper mines" OR "copper tailings" OR "mine tailings" OR "mining waste" OR "mine water" OR "mining wastewater" OR "mineral processing") AND ("circular economy" OR "resource recovery" OR "resource valorization" OR "resource valorisation" OR "waste valorization" OR "waste valorisation" OR "water reuse" OR "metal recovery" OR "material recovery" OR "industrial symbiosis" OR "reverse logistics" OR "circular logistics" OR "logistics network" OR "supply chain network" OR "circular supply chain") AND ("logistics" OR "supply chain" OR "industrial symbiosis" OR "circular economy" OR "environmental

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safety" OR "environmental risk" OR "environmental assessment" OR "life cycle assessment" OR "techno-economic assessment" OR "sustainable optimization" OR "multi-objective optimization" OR "resource management"))) AND NOT (SUBJAREA(IMMU) OR SUBJAREA(ARTS) OR SUBJAREA(DECI) OR SUBJAREA(MATH) OR SUBJAREA(MEDI) OR SUBJAREA(BIOC) OR SUBJAREA(AGRI) OR SUBJAREA(PHYS)) AND (DOCTYPE(ar) OR DOCTYPE(re) OR DOCTYPE(ch) OR DOCTYPE(bk)) AND PUBYEAR > 2006 AND PUBYEAR < 2027

The author confirms this expression as the original search formulation. The author reports conducting the search and selection between 8 June and 9 October 2026. The exact execution timestamp of the Scopus query is not separately recorded in S0 or S1; the stated interval is therefore reported as the documented search period rather than as a single execution date. Subject-area exclusions should be reported exactly as executed, without retrospectively substituting a logically different Boolean expression.

Study-level interpretation focused on the resource origin and mineralogical or aqueous matrix, processing and recovery approach, recovered output and quality evidence, possible receiving industry, logistical feasibility, and environmental and sustainability safeguards. Results from laboratory-scale or non-copper systems were not equated with site-validated copper-mining performance. A narrative synthesis was adopted because the reported endpoints and system boundaries were not sufficiently homogeneous to support a pooled meta-analysis. Table 1 summarizes the corresponding evidence and interpretive criteria.

Table 1. Review design, eligibility criteria, and documented study-selection workflow. The reported counts are traceable to Supplementary Tables S0 and S1; the preliminary copper-term exclusions are not duplicate removals.

Research Stage	Description
Research question	How are recovered resource flows from copper mining integrated with circular logistics networks, industrial symbiosis and environmental safety?
Review objective	Synthesize evidence on resource quantity and quality, circular network configurations, industrial exchange, and sustainability trade-offs.
Publication window	2007–2026 (inclusive; Scopus PUBYEAR > 2006 AND PUBYEAR < 2027).
Sources and search	Scopus search conducted by one reviewer (8 June–9 October 2026); initial retrieval S0 (n = 478); formal screening matrix S1 (n = 105). Preliminary copper-focused thematic filter: 373 records not advanced; 105 retained.
Eligibility	Copper-mining evidence or explicitly transferable mining context addressing resource recovery, logistics, industrial symbiosis or sustainability.
Selection	478 identified in S0; 373 not advanced after the copper-term pre-filter; 105 screened in S1; 33 title/abstract exclusions; 72 full texts assessed; 11 full-text exclusions; 61 included.
Evidence synthesis	Structured qualitative synthesis of flows, logistics, industrial symbiosis, environmental qualification, and cost/carbon/circularity trade-offs.
Reporting	PRISMA 2020 [44]; S0 preserves original retrieval, S1 preserves screening decisions; the 373-record preliminary thematic filter is documented in S0.

2.2. Review Transparency and Figure Provenance

The review was not prospectively registered, and no separately archived protocol is available. The Scopus expression, search-and-selection period, thematic pre-filter, screening decisions, and limitations of the retained records are reported in Section 2.1 and Supplementary Tables S0–S1. These materials permit reconstruction of the reported selection counts but do not establish the original query-execution timestamp, any pre-archive deduplication total, or a standardized study-level risk-of-bias score. PRISMA 2020 is used as a reporting guideline, not as evidence that the review methodology has been independently validated.

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Figure 1 is an author-prepared PRISMA 2020 selection diagram adapted from [44] using the screening totals documented in S0–S1. Figures 2–4 are author-directed conceptual illustrations. Their provenance and the specific use of generative AI are disclosed in Section 2.3 and in the corresponding figure captions. The diagrams illustrate the synthesis and proposed research agenda; they are not empirical observations or validated network models.

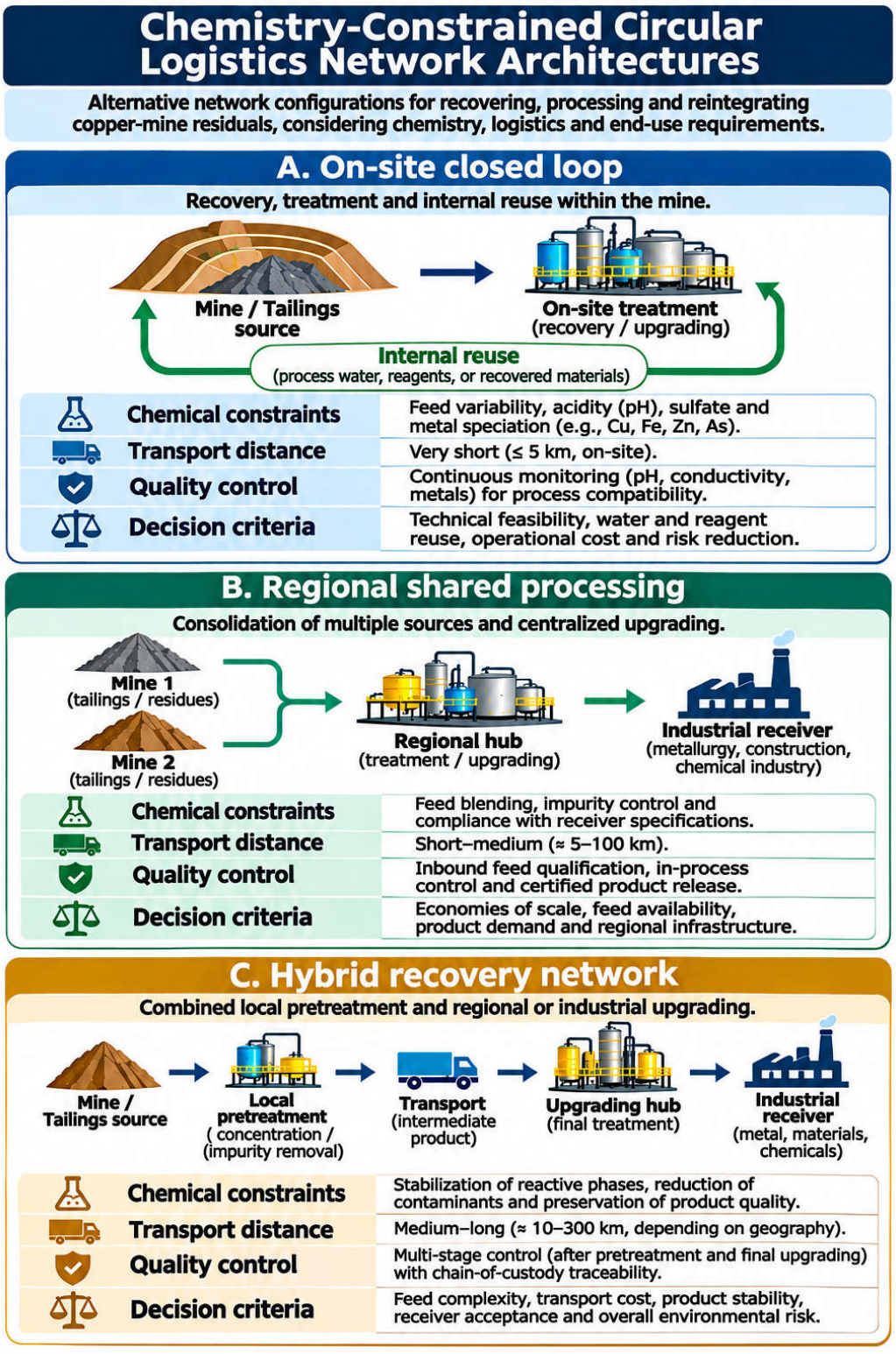


Figure 2. Chemistry-constrained circular logistics network architectures. Conceptual comparison of mine-site closed-loop recovery, regional shared processing and hybrid recovery networks. The architectures are author-derived alternatives informed by the literature on water–energy integration, mine-water recovery, on-site/off-

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site metal recovery and reverse logistics [33–35,37,40]. Their relative performance has not been empirically ranked. The illustration was prepared and refined with ChatGPT, GPT-6 (OpenAI, 2026), under author direction and scientific verification. It is a conceptual framework, not a validated predictive model or an independent source of empirical evidence.

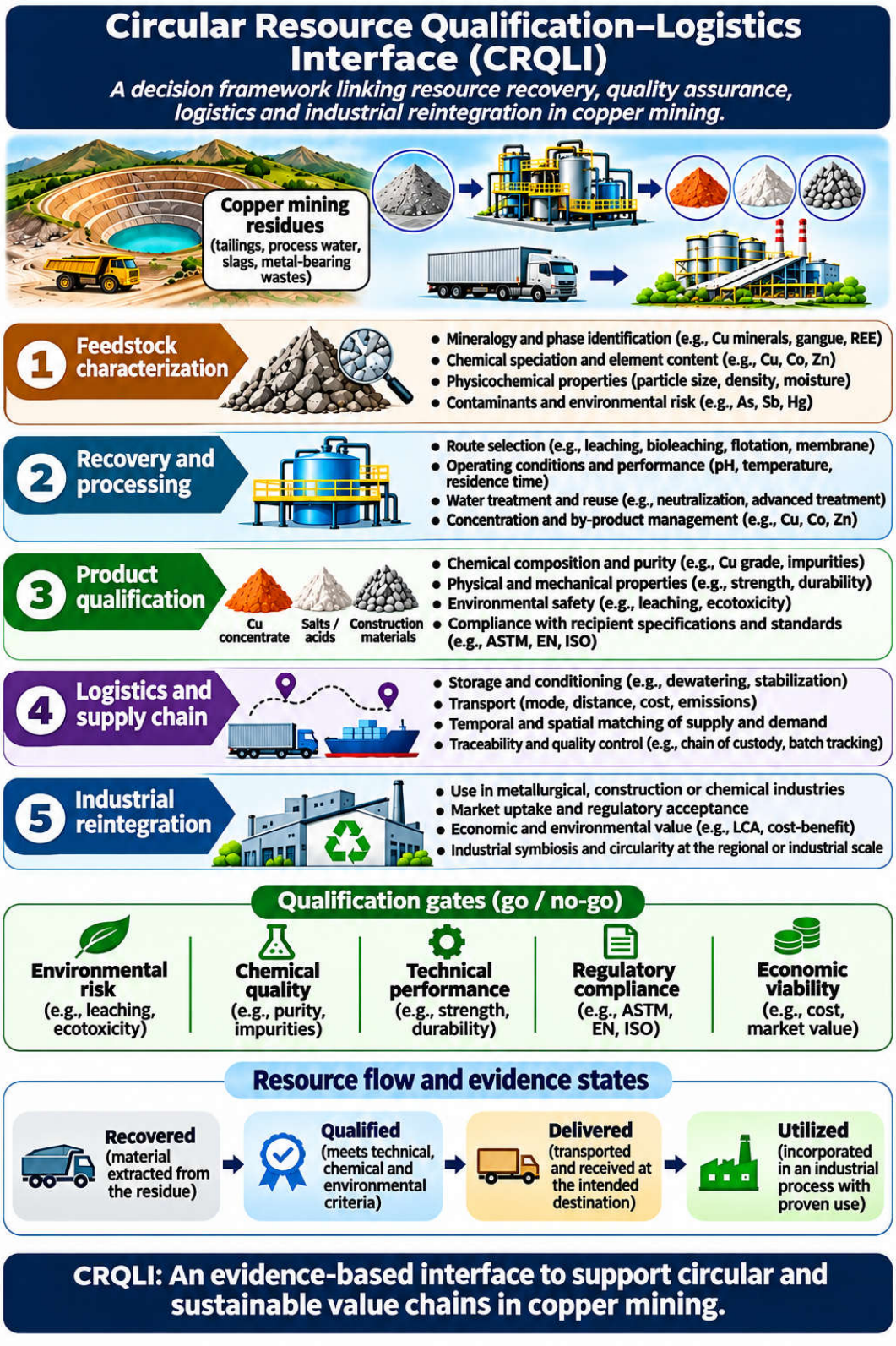


Figure 3. Circular Resource Qualification–Logistics Interface (CRQLI). Author-proposed decision architecture linking feedstock characterization, recovery, product qualification, logistics and industrial reintegration through environmental, chemical, technical, regulatory and economic gates. Recovered, qualified, delivered and utilized

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represent distinct evidence states rather than observed quantities. Conceptual synthesis informed by prospective life-cycle studies [41,42], laboratory material testing [21], water-circularity assessment under uncertainty [36] and secondary synthesis [43]; these sources motivate different components but do not validate the integrated framework. The illustration was prepared and refined with ChatGPT, GPT-6 (OpenAI, 2026), under author direction and scientific verification. It is a conceptual framework, not a validated predictive model or an independent source of empirical evidence.

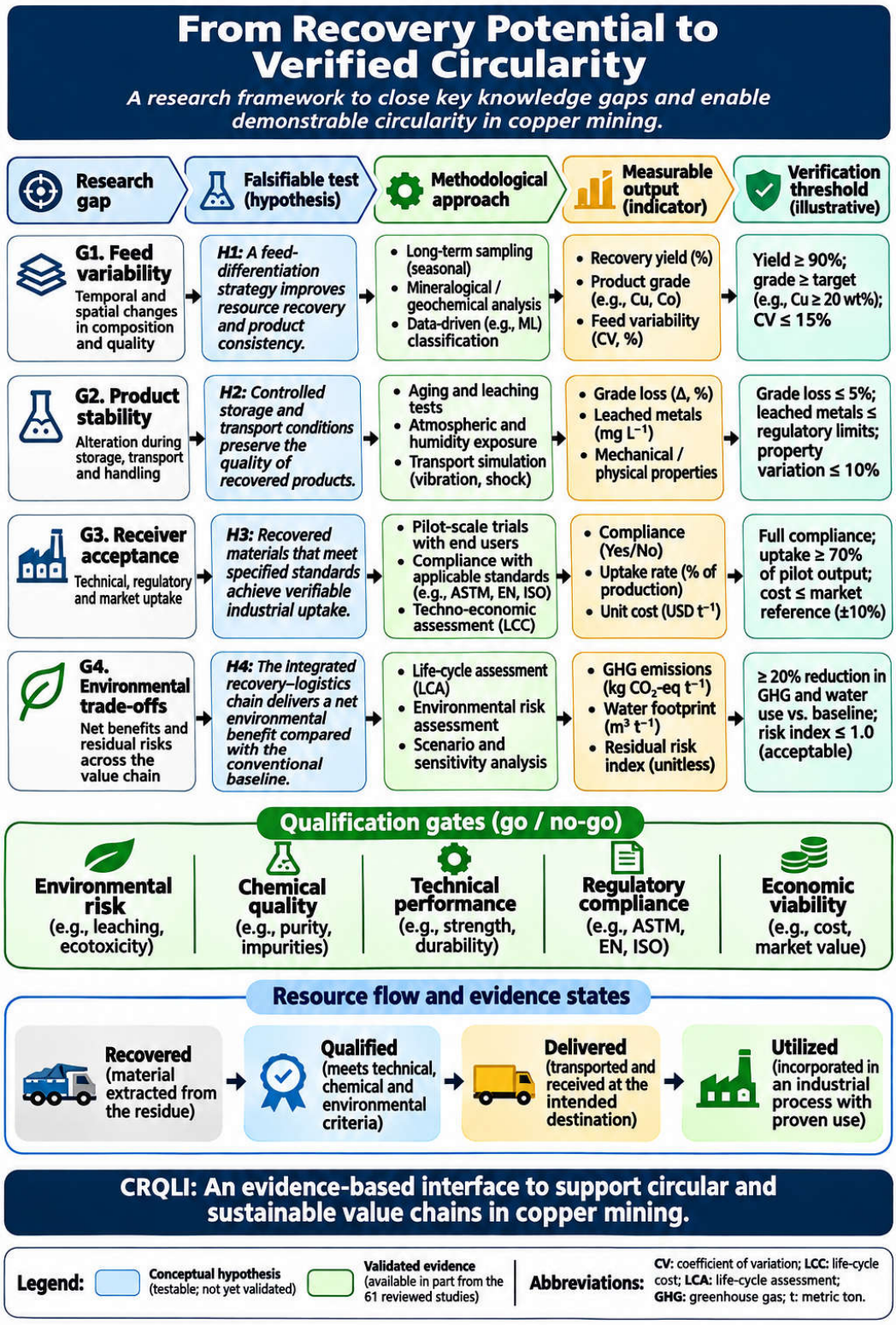


Figure 4. From recovery potential to verified circularity: research gaps, falsifiable tests, methodological approaches and candidate indicators. This author-derived research agenda connects feed variability, product

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stability, receiver acceptance and chain-level environmental trade-offs to measurable research designs [23,33,35,36,42]. Any numerical thresholds shown in the illustration are illustrative hypotheses only, not regulatory limits, validated performance targets or pooled findings from the 61-study corpus. The illustration was prepared and refined with ChatGPT, GPT-6 (OpenAI, 2026), under author direction and scientific verification. It is a conceptual framework, not a validated predictive model or an independent source of empirical evidence.

2.3. Use of GenAI Tools

ChatGPT, GPT-6 (OpenAI, 2026), was used to generate and refine the three author-directed conceptual illustrations presented in Figures 2–4. The author specified the scientific concepts and relationships, evaluated the resulting diagrams, and approved their final content. These illustrations are explanatory representations rather than validated predictive models or independent empirical evidence. Figure 1 was prepared separately by the author. The use of generative AI for the three illustrations is also identified in each relevant figure caption.

3. Results and Discussion

3.1. Evidence Base: From Resource Recovery to Operational Circularity

The 61 publications retained in S1 comprise 44 research articles, 14 reviews, and three book chapters published between 2013 and 2026. The archived S0 dataset (n = 478) and screening matrix S1 (n = 105) reconcile with Figure 1: 373 preliminary copper-term exclusions, 33 title/abstract exclusions, and 11 full-text exclusions. Study design limits inference. Reviews and conceptual studies may establish research directions but do not demonstrate operational transfer; likewise, laboratory recovery or product testing does not establish recipient acceptance. Table 3 therefore defines claim-level evidence thresholds rather than assigning a universal quality score to each publication. S1 contains study-specific inclusion rationales, while seven appraisal domains were considered qualitatively according to the claim and study design. Table 2 reports the bibliographic composition of the included corpus.

Table 2. Publication-type distribution of the 61 studies retained for qualitative synthesis, as recorded in Supplementary Table S1. Percentages are calculated using n = 61 as the denominator.

Document type (S1)	Number	Share of included publications
Article	44	72.1%
Review	14	23.0%
Book chapter	3	4.9%
Total	61	100.0%

The key distinction is between recoverability and reintegration. Recoverability concerns extraction, separation, immobilization, or conversion of a constituent. Reintegration additionally requires product conformity, an identified recipient, feasible delivery, and acceptable environmental performance. Prospective life-cycle assessments of sulfidic copper-tailings pathways [41,42] demonstrate why processing outcomes must be evaluated within broader system boundaries. Work on tailings-water recovery [35] likewise places reuse within an operational context. Together, these studies motivate a chain-level assessment of circularity, without themselves demonstrating a complete, verified resource-transfer network.

The corpus also includes three complementary reviews: Santoro et al. [1] synthesize membrane technologies relevant to copper mining; Arancibia-Zúñiga et al. [14] systematically examine leaching-based copper recovery from mining wastes; and Koucham et al. [43] integrate evidence on tailings characterization, environmental behavior, valorization, and dewatering. Their scope establishes an important boundary for the present synthesis: its distinct contribution is not another catalogue of treatment technologies or tailings products, but a systematic account of the interfaces linking chemically qualified outputs, network configuration, industrial demand and environmental safeguards. Table 3 summarizes the corresponding evidence and interpretive criteria.

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Table 3. Proposed claim-level evidence thresholds for circular-resource reintegration. Tiers A–E define the documentation required to support progressively different claims; they were not assigned as study-level ratings to the 61 included publications. The cited studies illustrate evidence types and limitations, not verified Tier A industrial reintegration.

Evidence tier	Typical study evidence	Permissible conclusion	Claim not supported without additional data
Tier A: documented reintegration	Measured product quality; identified recipient; traceable delivery, acceptance and use; environmental safeguards	Reintegration demonstrated only for the documented recipient, quantity, period and conditions	Does not establish wider transferability or network optimality. Recovery and LCA evidence [7,35,41,42] alone cannot establish Tier A.
Tier B: pilot/site feasibility	Pilot or operational observations; specified product and logistics boundary	Technical and logistical feasibility under the evaluated conditions	Does not establish sustained commercial uptake. Operational studies [33,35] inform feasibility; scenarios [36,41,42] remain conditional.
Tier C: experimental/prospective	Laboratory tests, material characterization, prospective LCA or cost scenarios	Potential route and conditional performance within tested assumptions	Cannot establish actual delivery or receiver uptake. Examples: [20,21,23,24,41,42,53].
Tier D: conceptual/secondary	Reviews, strategic analyses and proposed network architectures	Hypotheses, design options and research priorities	Cannot establish measured network performance or actual industrial transfer. Examples: [37–40,43].
Tier E: insufficient reporting	Missing methods, boundary definition or outcome data for a specific claim	Claim cannot be independently verified from the reported evidence	Absence of documentation is not evidence of non-occurrence. Interpretive criterion informed by reporting heterogeneity [21,38,41,42].
Cross-tier appraisal	Design-sensitive interpretation of experimental, field, modelling and review evidence	Conclusions limited to each study design and system boundary	No universal numerical ranking is inferred without comparable extraction and assessment; see [21,23,35,38,41,42].

3.2. Circular Resource Flows: Availability, Chemical Quality and Temporal Continuity

Copper operations generate resource streams with markedly different circular functions. Tailings and waste rock may contain residual copper and associated elements, process waters may provide a reusable hydraulic resource, and slags or mineral-rich residues may act as precursors for industrial materials. These streams are not interchangeable inventories. Their recoverable fraction depends on mineralogy, speciation, particle-size distribution, water chemistry and the performance of a specific recovery route. Characterization of copper-mine waste and its implications for metal mobility and recovery is central to [29], whereas Lam-Esquenazi et al. [45] examine the geochemical screening of critical elements in Chilean copper tailings. These contributions illustrate the need to distinguish total element abundance from technically accessible, environmentally manageable supply. Source characterization and reprocessing case studies include abandoned copper- and

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manganese-mine wastes, Norwegian tailings, Au–Cu tailings and Chilean geochemical profiles; these cases illustrate feed heterogeneity rather than a common recovery yield [46–49].

At the material-flow interface, the recovery of cobalt and copper from flotation tailings investigated by Lutandula and Maloba [7], together with the assessment of cobalt extraction from copper-mining tailings reported by Ramírez-Arias et al. [50], illustrates potential pathways for generating recoverable resource streams. The prospective assessments reported in [41,42], however, require a wider accounting boundary: a recoverable mass is not automatically a net environmental gain when reprocessing energy, reagents, secondary residues and displaced primary production are considered. For comparison across studies, the analytically relevant quantities are feed throughput, recoverable yield, qualified product output, residual output and the destination of each stream; values not reported or extractable from the assessed full-text publications are not inferred.

Water has a distinctive logistical profile. Its movement depends not only on volume but also on salinity, suspended solids, dissolved metals, temporal demand and elevation-related energy requirements. Araya et al. [33] explicitly connect tailings-water management to the water–energy nexus and operational flexibility, whereas Schwarz et al. [35] investigate a zero-liquid-discharge-oriented system intended to maximize tailings-water reuse. Vargas et al. [36] develop and apply a water-circularity assessment methodology incorporating uncertainty and sensitivity analysis; their work does not independently document chain-of-custody records or final-user acceptance of transferred resources. Read together, these studies suggest that water circularity should be evaluated as a time-dependent allocation problem: the useful output is water of adequate quality delivered to an identified process at the time and location it is needed. Copper-concentrator waste minimization through combined preconcentration and fine-tailings utilization is also examined as a process-integration pathway, rather than evidence of verified downstream offtake [51]. Table 4 summarizes the corresponding evidence and interpretive criteria.

Table 4. Resource-specific qualification constraints and logistics interfaces identified across the reviewed evidence. The configurations are analytical interpretations, not empirically optimized networks; citations support the stated material, water-quality, or processing constraints.

Recovered flow	Minimum quality/quantity evidence	Logistics interface	Recipient / environmental gate	Supporting literature (evidence scope)
Reclaimed tailings water	Flow, salinity, metals, recovery, demand quality	Storage, elevation, transfer energy, demand timing	Process-water acceptance; concentrate fate	[33,35,36]—Water-treatment and circularity studies; recipient delivery not demonstrated.
Copper / cobalt concentrates	Mineralogy, grade, yield, impurity profile	On-site upgrading vs off-site processing	Refinery specifications; residue handling	[7,45,50]—Metal recovery and processing studies; refinery offtake not demonstrated.
Zn/Cu-bearing acid waters	Selective recovery and product chemistry	On-site / off-site treatment; intermediate storage	Acceptable metal product; residual-water quality	[34,58]—Selective treatment evidence; downstream use not verified.
Tailings-derived binders	Particle and phase chemistry; mechanical performance	Segregation, conditioning, haulage, batch consistency	Construction specifications; leaching and durability	[20,21,23–25]—Material testing studies; industrial qualification not implied.

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Tailings and slag concrete	Composition, replacement rate, material performance	Bulk transport, blending and recipient capacity	Material standards; environmental release	[25–27,29]—Materials studies; long-term service safety remains conditional.
Tailings-derived reactive mineral fraction	Mineralogy, particle-size distribution, reactivity, impurity speciation, durability and leaching	Dewatering, classification, batch segregation and stability during storage	Recipient-specific binder specification and exposure-dependent release	[20,23,53,55]—Mineralogical and binder studies; no certified recipient claimed.
Critical-element co-products	Assayed element inventory, phase association, selective recovery and product purity	Concentration, regional upgrading and traceable intermediate shipments	Metallurgical acceptance and residual-disposal boundary	[45,46,58]—Recovery/characterization studies; regional delivery not proven.
Slag and composite residues	Phase composition, residual metal inventory, grading and leaching behavior	Segregation, bulk logistics and proximity to end-user	Product durability and contaminants under service exposure	[22,25,30,31]—Slag and residue studies; actual offtake not inferred.

3.3. Circular Logistics Networks: Spatial Configuration, Reverse Flows and Traceability

Logistics becomes analytically consequential once recovered streams leave the processing boundary. A circular network may include generation points, characterization and segregation, on-site or shared recovery facilities, intermediate storage, transport corridors, industrial receivers and residual-management destinations. Its feasibility depends on spatially dispersed volumes, product stability during handling, transport mode, storage constraints and the synchronization of supply with industrial demand. [40] explicitly consider reverse logistics in copper-related heap-leaching operations; Jamett et al. [37] examine Industry 4.0 as an enabling approach to circular copper mining. These studies are particularly relevant because they move the analysis from what can be recovered to how material and information may circulate through operations.

For aqueous flows, on-site versus off-site treatment is a chemically conditioned logistics decision rather than a purely geographic one. Vecino et al. [34] examine selective precipitation and ion exchange for copper- and zinc-bearing acid mine waters and explicitly frame on-site/off-site management options. Their study provides a useful bridge between separation chemistry and network architecture: the form in which a metal leaves a treatment stage affects storage requirements, transportability, downstream processing and potential recipients. A concentrated recoverable product and an untreated dilute stream may require entirely different logistics even when their contained metal mass is comparable.

The review distinguishes three configurations as analytical alternatives rather than validated universal optima: on-site recovery and internal reuse; shared or regional treatment followed by external delivery; and hybrid networks combining local pretreatment with centralized upgrading. Their relative merits depend on flow volumes, transport distances, quality stability, receiving capacity and environmental controls. Assessment of the included full texts did not yield a sufficiently comparable, spatially and temporally resolved multi-site dataset to rank these configurations quantitatively. Table 5 summarizes the evidence and decision criteria, while Figure 2 illustrates the conceptual alternatives rather than observed performance rankings.

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Table 5. Conceptual circular-logistics network configurations and chemistry-dependent feasibility conditions. Receiver specifications and matching requirements are proposed evaluation criteria rather than documented commercial offtake.

Network configuration	Material-flow logic	Chemical / environmental gate	Logistics decision variable	Supporting literature (evidence scope)
Mine-site closed loop	Treat and reuse water or recover resources within the operating boundary	Fit-for-process water quality; management of concentrate and secondary residues	Demand timing, elevation, storage and energy use	[33,35,36]—Water reuse and circularity evidence; configuration is synthesized.
On-site pretreatment + off-site upgrading	Stabilize or concentrate a recoverable stream before transfer	Speciation, impurities and intermediate-product stability	Transported mass, handling constraints and receiver specification	[7,34,50,59]—Recovery and treatment studies; route is proposed.
Regional shared processing	Aggregate compatible streams from multiple generation points	Feed variability, blending compatibility and traceable batch qualification	Hub location, collection radius, inventory and plant utilization	[37,38,40]—Circular logistics/decision-support literature; hub is conceptual.
Mine-to-industry symbiosis	Supply qualified tailings-derived feedstock to a non-mining receiver	Mechanical fitness, contaminant release, durability and reproducibility	Recipient capacity, bulk transport, storage and acceptance testing	[20,23–25,31]—Materials and reuse studies; exchange is prospective.
Hybrid recovery + residual management	Separate value-bearing output from residual fractions with distinct destinations	Mass-balance closure and long-term fate of residuals	Parallel product and residual routes; burden shifting	[41,42,60]—Prospective impact studies; residual route is synthesized.
Distributed qualification hubs	Condition, characterize and aggregate compatible resource batches	Speciation, moisture and blending compatibility	Collection radius, storage time, rejection rate and hub utilization	[26,27,29,43]—Characterization and reviews; hub is hypothetical.
Digitally traceable exchange	Connect feed lot, recovery batch, carrier and recipient acceptance	Chemical identity and quality retained across handovers	Chain-of-custody, digital batch records and delivered mass	[37,39,40]—Logistics/digital context; custody system is proposed.
Multi-site scenario allocation	Compare decentralized, centralized and hybrid transfer networks	Prevent dilution of high-risk lots and unqualified external transfer	Transport load, distance, demand, residual routing and uncertainty	[38,40,59]—Network and reverse-logistics context; no optimized site network claimed.

3.4. Industrial Symbiosis: Fit-for-Purpose Matching of Recovered Solids and Recipient Industries

Industrial symbiosis requires a stronger evidentiary standard than the identification of a possible application. The receiving industry must be able to use a material of reproducible composition and sufficient performance without unacceptable contaminant release or an adverse life-cycle trade-off. The copper-tailings construction-material studies provide a concrete test case. Reference Kanaan and Alam [24] examines copper–molybdenum tailings in high-performance mortars; Fattahi et al. [23] investigates alkali-activated binders derived from copper-mine waste; Romero et al. [25] examines concrete incorporating copper tailings and slag; and Mohamed Lefdhil et al. [52] investigates geopolymerization of iron-rich copper tailings. These papers establish technical routes toward possible industrial use, but a successful material test does not itself establish sustained commercial uptake,

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a contracted off-taker or an operating logistics network. Other studies examine waste-mixture valorization, flotation-tailings/fly-ash combinations and integrated iron-bearing tailings processing; transfer to copper-specific receiving industries requires separate verification [22,54,55].

Chemical and environmental qualification remains decisive. Cai et al. [21] investigate stabilization/solidification of copper tailings using industrial-waste-derived cementing materials and evaluate leaching-related behavior. Makangila et al. [29] emphasize elemental speciation and fractionation, which influence mobility and the interpretation of environmental risk. Together, these studies imply that a receiving-industry match should be screened on at least four levels: feedstock chemistry, engineering performance, environmental release under relevant exposure conditions and consistency of supply. A nominally circular exchange that fails any one of these tests may simply transfer a liability from the mine to another sector.

The potential for symbiosis extends beyond construction products. Copper slags and metal-bearing residues may be redirected toward recovery or processing pathways, as reviewed by [2]. Nevertheless, the review does not equate the number of proposed uses with the number of verified industrial partnerships. No aggregate count of operational exchanges is reported because the full-text evidence does not establish a consistent definition and comparable inventory of verified exchanges across the included studies; S1 records eligibility rationales rather than standardized commercial-offtake outcomes. Table 6 summarizes the corresponding evidence and interpretive criteria.

Table 6. Proposed resource–recipient matching criteria for industrial symbiosis in copper mining. Supporting references address relevant material properties, environmental constraints, or assessment approaches; they do not establish verified recipient acceptance.

Recovered stream	Potential receiving system	Qualification criteria	Supporting literature (evidence scope)
Copper-bearing concentrate	Metallurgical or hydrometallurgical processor	Grade, impurities, mineralogy, moisture, batch traceability	[7,45,50]—Recovery and concentrate studies; recipient is potential.
Tailings-derived mineral fraction	Construction materials and engineered fill	Particle size, mechanical performance, contaminant release and durability	[20,21,23–25,53]—Materials characterization and performance; recipient is potential.
Recovered process water	Mine operations or compatible industrial users	Use-specific salinity, metals, scaling potential and reliability	[33,35,36]—Water-treatment and circularity studies; use is conditional.
Secondary process residue	Further recovery or controlled stabilization	Residual metal content, phase stability, leaching and long-term fate	[34,58]—Selective recovery studies; disposition is conditional.
Tailings-derived alkali-activated binder	Construction-material manufacturers	Binder reactivity, mechanical strength, durability, aging and leaching	[21,23,53]—Binder and leaching studies; acceptance is unverified.
Tailings–slag concrete	Precast and infrastructure materials	Grading, mixture ratio, durability, contaminant release and batch variability	[24,25]—Concrete performance studies; market uptake unverified.
Qualified reclaimed water	Mine-site processing users	Conductivity, salinity, dissolved metals, solids and process tolerance	[33,35,36]—Water-treatment studies; acceptance requires site data.

3.5. Environmental Safety as a Constraint on Network Design

Environmental safety is not a final compliance check added after a logistics network has been selected; it can determine whether a material is suitable for movement at all. Copper-tailings characterization and geochemical behavior influence the permissible destination and treatment intensity, particularly when potentially toxic elements may be mobilized during weathering, processing or

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incorporation into new products. Makangila et al. [29] link speciation and fractionation to metal recovery and environmental implications, while Cai et al. [21] connect stabilization performance with leaching behavior. The implications for logistics are direct: transport and storage decisions should distinguish chemically stable products from reactive or incompletely characterized residues. Related studies address copper leaching from historic waste dumps and metal immobilization in mine wastes, emphasizing that extraction and environmental stabilization are different endpoints [56,57].

This constraint also applies to water. The value of reclaimed water depends on the requirements of its intended use, while a high water-recovery fraction may be accompanied by concentrate production and additional energy demand. [35] and Araya et al. [33] provide complementary perspectives on water-reuse infrastructure and water–energy interactions. A credible circular network therefore needs an explicit destination for rejected salts, residual solids and other secondary streams, rather than treating these outputs as outside the system boundary.

A critical evidence gap emerges from the full-text synthesis: the included studies do not consistently report comparable, traceable evidence covering quality assurance at transfer, stability during storage, recipient-specific acceptance and post-transfer environmental monitoring. This is a limitation of the published and extractable evidence across heterogeneous designs; it does not establish that such practices were absent at the investigated sites. Table 7 summarizes the corresponding environmental safeguards and reporting requirements.

Table 7. Environmental qualification requirements for proposed circular logistics pathways. Indicators are author-derived decision criteria informed by the cited evidence, not measured performance of complete logistics networks.

Pathway decision	Environmental evidence needed	Potential burden shifting	Minimum reporting expectation
Store and aggregate recovered solids	Leaching under plausible storage conditions; dust and runoff controls	Exposure and contaminant migration during stockpiling	Report storage duration, moisture, containment, runoff and dust controls, and monitoring. Mineralogical and leaching studies motivate the safeguards but do not validate storage-duration limits [11,26,27,29].
Transport to an external processor	Physical and chemical stability during handling; packaging requirements	Transport emissions, spills and secondary handling	Report mode, distance, loading, containment, material condition and incident controls. Hazard characterization and prospective life-cycle assessments inform risk and burden boundaries; they do not validate a specific transport operation [21,29,41,42].
Reuse mineral products	End-use release, aging and service-life performance	Long-term release to soil and water	Report product formulation, exposure-relevant leaching, aging, service conditions and uncertainty. Laboratory strength and leaching evidence does not establish long-term field safety or commercial acceptance [21,23–26,53].
Reuse recovered water	Fit-for-purpose water chemistry and concentrate fate	Transfer of salts or residual contaminants to another process	Quality specification, reuse volume and residual destination. Evidence anchors: [33,35,36].

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Mix tailings with distinct geochemical signatures	Lot-level mineralogy, speciation and acid-generating potential	Blending can mask reactive fractions and displace release risk	Blend ratio, feed identity and post-blend leaching. Evidence anchors: [26,27,29,43].
Transform tailings into cementitious products	Curing chemistry, aged leachability, weathering and service-life exposure	Immobilized contaminants can remobilize with changing pH or aging	Exposure-relevant leaching and durability. Evidence anchors: [21,23–25,53].
Selectively recover metals from mine water	Dissolved speciation, recovery selectivity and residual chemistry	Reagents, concentrates and residual brines can shift burdens	Mass balance and residue fate. Evidence anchors: [34,58].

3.6. Joint Sustainability Assessment: Cost, Carbon, Risk and Circularity

A circular route can outperform disposal on one indicator while performing worse on another. Adrianto and Pfister [41] and Adrianto et al. [42] assess environmental implications of copper-tailings reprocessing pathways, providing a basis for discussing burden shifting rather than presuming that greater recovery is inherently preferable. Reference Marín et al. [59] addresses the estimation of processing costs for valuable-element recovery from mine tailings, while reference Monardes and Sepúlveda [38] applies multicriteria analysis to tailings-dam management. Their contributions point toward a common decision space involving resource recovery, environmental risk, cost and operational feasibility. An earlier copper-sector life-cycle case study further illustrates the relevance of system-boundary choices to sustainability assessment [60].

A robust comparison should adopt a clearly specified functional unit and system boundary. For water, the functional output may be a unit of water meeting a defined reuse specification at the point of demand; for recovered metals, a quantity of saleable or process-compatible product; and for construction materials, a performance-equivalent quantity of the substituted product. These are proposed comparison principles, not harmonized functional units reported across all 61 studies. The boundary should include recovery, conditioning, storage, transport, displaced primary production where justified, and treatment or disposal of remaining residues.

Decarbonization and circularity may interact but should not be conflated. Negrete et al. [61] examine socio-environmental implications of decarbonization in copper and lithium mining, illustrating why energy-transition strategies require attention to broader consequences. Similarly, strategic circular-economy adoption in copper mining is addressed by [39], but organizational commitment alone does not quantify avoided emissions or verified material reintegration. The evidence therefore favors multicriteria interpretation over any unqualified claim that circular logistics is necessarily lower-carbon or lower-cost. Mining-sector circular-economy approaches in the Democratic Republic of Congo offer an additional governance context, without establishing the performance of a specific copper-tailings logistics network [62]. Table 8 summarizes the corresponding evidence and interpretive criteria.

Table 8. Distinction between process-level recovery measures and proposed chain-level circularity outcomes. The proposed verification gates are conceptual and have not been operationally validated.

Assessment axis	Conventional process-level metric	Chain-level indicator proposed here	Interpretive caution
Recovery	Extraction or removal efficiency	Qualified resource delivered per unit feed	Recovery alone does not verify reuse. Evidence anchors: [7,14,42,50].

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Logistics	Unit-operation throughput	Origin–destination flow, storage and transport requirements	No universal network optimum inferred. Evidence anchors: [37,38,40,59].
Recipient qualification	Potential material application	Named receiver specification and documented product acceptance	Lab performance is not an offtake agreement. Evidence anchors: [20,23–25].
Environmental safety	Point-of-treatment compliance	Leaching, stability and residual fate across transfer	Burden shifting must be assessed across handling, use and residual fate; illustrative. Evidence anchors: [21,26,27,29,43].
Sustainability	Isolated treatment cost	Comparable cost, emissions, water, risk and circularity	Functional unit and boundaries must match. Evidence anchors: [41,42,60,61].
Traceability	Recovered product quantity	Documented custody and verified final use	Proposed chain-of-custody and end-use verification metric; supports water-circularity indicators and uncertainty analysis, not empirical tracking of material lots, recipient acceptance or final uptake. Evidence anchors: [36,37,40].
Product qualification	Nominal recovery yield	Accepted output mass meeting named recipient specification	No qualified yield without acceptance criteria. Evidence anchors: [20,21,23,24,53].
Verified industrial exchange	Count of proposed end uses	Identified off-taker, accepted mass and documented duration of exchange	Proposed receiver-verification criterion, not an observed industrial transfer demonstrated by the cited literature. The sources provide circularity, logistics or decision-support context [37–40].
Water circularity	Recovered water volume	Demand-matched volume at the required quality and time	Treatment outlet is not necessarily reuse point. Evidence anchors: [33,35,36].
Environmental burden shifting	Isolated project cost or single LCA category	Comparable cost–carbon–risk–circularity outcomes under a common boundary	Do not rank studies with different functional units. Evidence anchors: [41,42,61].

3.7. Cross-Dimensional Synthesis and the Unresolved Chemistry–Logistics Interface

The principal finding of this review is not a shortage of candidate recovery technologies, but a discontinuity in the evidence connecting recovery to industrial reintegration. Across the 61 publications catalogued in Supplementary Table S1, studies address mineralogical characterization, metal

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extraction, water reclamation, secondary construction materials, environmental performance and circular-economy management. These contributions illuminate different parts of the same physical system, yet their reported outcomes are not readily interchangeable. A recovery yield measures separation at a process boundary; material compliance establishes suitability for a specified use; delivered quantity reflects logistical performance; and documented incorporation establishes productive uptake. The distinction is consequential because a technically successful process can still generate an output that lacks a qualified receiver, arrives outside the demand window or carries an unresolved residual liability. This is an inference from the scope and reporting of the available corpus, not evidence that integrated operations do not exist elsewhere [36,40,42].

The chemistry–logistics interface is therefore best understood as a set of coupled feasibility conditions rather than a linear hand-off between treatment and transport. Mineral assemblage, metal speciation and contaminant mobility determine what can be separated, stabilized or blended; the resulting quality distribution determines which receivers and transport routes are admissible. Storage duration, moisture exposure and batch mixing may in turn alter the properties on which initial qualification depended. For reclaimed water, the corresponding constraints include salinity, scaling potential, dissolved metals, hydraulic elevation and the temporal coincidence of supply with process demand. The studies on selective metal recovery from mine waters, water–energy interactions and tailings-derived materials provide complementary foundations for this interpretation, but do not collectively furnish a validated multi-site routing model [21,33–35].

To make these dependencies explicit, we propose the Circular Resource Qualification–Logistics Interface (CRQLI). Its contribution is an auditable decision architecture that requires a candidate flow to pass source characterization, process-output measurement, recipient-specific qualification, logistics feasibility, environmental acceptability and verified-use gates. A failed gate does not erase technical recovery; it changes the defensible claim from circular reintegration to conditional recovery potential. Table 9 specifies the gates, while Table 10 separates the corresponding chain-level indicators and denominators. The framework draws on the complementary evidence for reprocessing, environmental assessment, water circularity and reverse logistics [7,36,40,41]. CRQLI remains a testable synthesis, not a field-validated optimization algorithm or a demonstrated industrial network. Figure 3 presents the proposed CRQLI stages, qualification gates and distinct evidence states.

Table 9. Proposed CRQLI qualification gates linking feedstock characterization, product conformity, logistics feasibility, and verified downstream utilization. The gates constitute an author-derived assessment framework.

Decision gate	Evidence required	Go/no-go implication for the network	Verification status
G1. Resource inventory	Measured throughput, recoverable fraction, temporal variability and material balance	Size facilities and distinguish continuous from intermittent flows	Must be reported or measured; not inferred from resource potential. Evidence anchors: [11,45–47,49].
G2. Product qualification	Chemical composition, speciation, impurity limits and fit-for-purpose performance	Select treatment intensity and admissible receiving process	Laboratory performance is not equivalent to product certification. Evidence anchors: [21,23,24,29,53].
G3. Storage and transport compatibility	Stability, moisture/physical form, handling risks and possible release	Choose on-site versus off-site upgrading, packaging and storage	Requires route-specific evidence; no universal thresholds assumed. Evidence anchors: [26,27,29,40].

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G4. Recipient acceptance	Technical specifications, demand volume, regulatory conditions and verified off-taker	Establish viable origin–destination link and exchange continuity	Requires actual recipient specification and acceptance records; cited logistics/network studies motivate the gate but do not independently demonstrate offtake. Evidence anchors: [20,24,37,38,40].
G5. Environmental safeguard	Leaching/aging, residual fate, emissions and system boundary	Reject pathways that relocate environmental burdens	Comparative assessment should include displaced processes and residuals. Evidence anchors: [26,27,29,41,42].
G6. Verified reintegration	Traceable quantity, destination, duration and monitoring after transfer	Count delivered, accepted and used output as achieved circularity	Prospective scenarios must not be reported as observed transfers. Evidence anchors: [37,38,40,42].
G7. Storage–quality feedback	Time-resolved composition and exposure during storage and transport	Adjust pretreatment, routing and storage when quality changes	Prospective criterion; paired transport and acceptance observations needed. Evidence anchors: [21,26,27,29].
G8. Verified circular displacement	Accepted mass, replaced virgin feed, residual fate and baseline disposal	Count only traceable delivered outputs and avoid double counting	Requires documented uptake or explicitly prospective counterfactual. Evidence anchors: [41,42,60,61].

Table 10. Proposed chain-level circularity indicators, operational definitions, and minimum verification evidence. Indicators are author-derived and must not be interpreted as pooled estimates or demonstrated commercial reintegration.

Proposed indicator	Operational definition	Required verification	Supporting literature (evidence scope)
Qualified-output fraction	Mass meeting a named receiver specification / recovered mass	Batch assays, uncertainty, rejected fraction	[20,21,23,24,53]—Product testing; indicator is author-proposed.
Verified reintegration fraction	Mass accepted and used by receiver / qualified mass dispatched	Delivery receipts, acceptance tests, production incorporation	[37,38,40–42]—Logistics/LCA context; uptake metric is author-proposed.
Fit-for-purpose water delivery	Volume meeting process specification at point and time of use / volume reclaimed	Flow metering, quality monitoring, demand schedule	[33,35,36]—Water circularity evidence; delivery metric is proposed.
Logistics-adjusted net benefit	Avoided primary burden minus recovery, conditioning, transport and residual burdens	Consistent functional unit, system boundary and sensitivity analysis	[41,42,60,61]—Prospective LCA evidence; benefit metric is proposed.
Residual-fate completeness	Accounted residual output / total generated residual output	Phase-resolved balances and documented destination	[26,27,29,41,42]—Material and LCA evidence; accounting metric is proposed.

The indicators in Table 10 are deliberately non-equivalent. Reporting recovered mass as if it were qualified, delivered or actually used mass would conceal rejection, conditioning losses and supply–demand mismatch. Their interpretation also requires a counterfactual: displacement of virgin

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feedstock cannot be credited without establishing functional equivalence and the fate of residual streams. Consequently, an apparent gain in material circularity may be offset by additional energy, transport, reagents or contaminant-management burdens. These are hypotheses to be evaluated with comparable inventories, not pooled numerical findings from the present corpus [36,42].

3.8. Evidence Maturity, Limitations and Research Priorities

The maturity of the evidence is uneven, and that unevenness should shape the conclusions drawn from it. Experimental studies can demonstrate extraction or material performance under specified conditions; prospective life-cycle assessments can identify scenario-dependent environmental trade-offs; and strategic or review articles can organize concepts and plausible pathways. None of these designs, on its own, verifies sustained industrial exchange. In particular, prior reviews of copper-waste leaching and tailings management should inform the interpretation of primary studies rather than be counted as independent replications [14,43]. The evidence hierarchy in Table 3 therefore serves as a safeguard against converting bibliographic breadth into unwarranted operational certainty.

The next research step is not simply to add further recovery trials, but to join measurements that have conventionally been reported in isolation. Four linked tests are especially valuable: (i) whether source variability changes the fraction meeting a named receiver specification; (ii) whether storage and transport alter that fraction before acceptance; (iii) whether geographically and temporally constrained demand changes the preferred location of treatment or upgrading; and (iv) whether verified substitution still provides a net benefit once transport, residual management and uncertainty are included. Table 11 translates these needs into research priorities, and Table 12 proposes falsifiable study designs. These proposals connect the strengths of prospective assessment, reverse-logistics analysis, water-loop engineering and material qualification without asserting that any single cited study has already demonstrated the entire chain [23,35,40,42]. Figure 4 translates these gaps into falsifiable study designs and candidate verification indicators; the depicted thresholds are illustrative, not validated decision limits.

Table 11. Evidence gaps and research priorities at the chemistry–logistics interface. Proposed research directions are derived from the qualitative synthesis; cited publications motivate the gaps but do not validate the proposed solutions.

Evidence gap	Required study design or reporting	Decision enabled
Uncertain recoverable inventory	Time-resolved feed and output mass balances, chemical variability	Facility capacity and reliable supply. Evidence anchors: [11,45–47,49].
Unqualified secondary materials	Recipient-specific product standards, exposure-relevant leaching and aging, and batch variability; distinguish short-duration laboratory tests from long-term field performance.	Recipient acceptance and safe transport. Evidence anchors: [21,23,24,26,29,53].
Disconnected network models	Spatially explicit flow-quality-demand scenarios	Compare on-site, shared and hybrid configurations under explicit spatial, quality and demand constraints. The cited works motivate reverse-logistics and decision-support scenarios, not a validated regional optimum [37–40].

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Incomplete impact boundaries	Comparative LCA/TEA including transport and residual fate	Avoided burden and net circular value. Evidence anchors: [41,42,60,61].
Weak proof of reintegration	Documented receiving industry, volumes, contracts or monitored use	Distinguish modeled or proposed downstream pathways from documented delivery, recipient acceptance and actual use. The cited works provide management and logistics context, not verified industrial uptake [37–40].
Quality drift during storage	Link aging/leaching tests to realistic storage and transport conditions	Determine allowable storage duration and handling form. Evidence anchors: [21,26,27,29].
Unverified industry exchange	Track batch identity, recipient specification, delivery and material substitution	Distinguish plausible symbiosis from documented industrial uptake. Evidence anchors: [37–40].
Incommensurable sustainability indicators	Harmonize functional units, allocation, substitution and uncertainty	Test whether inclusion of logistics and residual fate changes prospective sustainability rankings under comparable boundaries [36,41,42,60,61].
Chemistry–network disconnect	Jointly evaluate geochemical variability, logistics, acceptance and release thresholds	Empirically test the proposed CRQLI interface rather than assume validation. Evidence anchors: [37,40,42].

Taken together, Tables 3–12 distinguish findings interpreted from the included full-text publications from analytical requirements proposed by the author. The tables are neither a census of implemented circular networks nor a numerical ranking of commercial technologies. In particular, Tier A in Table 3 defines the evidence needed to claim documented reintegration; it is not attributed to an illustrative scenario or conceptual study. The available S1 justifications substantiate inclusion and relevance but do not independently certify operational uptake or provide uniform study-level quality ratings. Future research should report comparable full-text outcomes, explicitly distinguish copper-specific from transferable findings and quantify uncertainty before attempting cross-route meta-analysis or network optimization.

Table 12. Falsifiable study designs for evaluating resource qualification, logistics, and recipient acceptance in copper-mining circular networks. Hypotheses and primary outcomes are proposed by the author; cited studies provide context rather than direct validation.

Testable hypothesis	Required study design	Primary outcome	Supporting literature (evidence scope)
Time-varying feed-to-demand matching	Seasonal copper-tailings water chemistry and hourly process-water demand	Quality-compliant delivery volume, pumping energy and unmet demand	[33,35,36]—Water treatment/circularity; hypothesis not tested as stated.
Storage-induced qualification loss	Replicated accelerated/field aging of recovered solids before and after transport	Specification failures, leachate chemistry and rejected mass	[21,23,26,27,29]—Materials durability/leaching; storage test is proposed.

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Receiver-constrained network selection	Compare on-site processing with regional hubs using actual offtake constraints	Accepted delivered mass, cost, GHG burden and residual liability	[37–40]—Reverse-logistics/decision-support; receiver-constrained comparison untested.
Prospective versus realized substitution	Couple prospective LCA with documented receiver acceptance and displacement factors	Net avoided impact with sensitivity to substitution and transport	[41,42,60,61]—Prospective LCA; realized substitution must be verified.

4. Implications for Technology Selection and Implementation

4.1. Reframing the Unit of Circular Performance

The decision-relevant unit in a circular copper-mining system is not the recovery unit operation but the qualified, delivered and demonstrably utilized resource flow. A process may achieve high laboratory extraction or separation efficiency while yielding a product that is chemically unsuitable for its intended receiver, available at an incompatible rate, or associated with secondary residuals that remain unmanaged. Consequently, treatment performance, product qualification, logistical deliverability and actual industrial uptake must be evaluated as sequential and potentially constraining conditions rather than interchangeable proxies for circularity [34,36,42].

This interpretation has an immediate implication for study design: recovered mass should be reported alongside its chemical specification, uncertainty, destination, temporal availability and residual fate. Where destination-specific standards or acceptance data are unavailable, the result should be described as a technically recoverable fraction or prospective product, not as an achieved circular exchange. The distinction is particularly important for heterogeneous tailings and chemically variable mine-water streams, for which mineral assemblage, element partitioning and process history can determine both recovery potential and downstream suitability [11,29,45].

4.2. Chemistry-Constrained Logistics as a Design Principle

Circular logistics should be treated as a chemically constrained network rather than a generic transportation problem. Network nodes represent generation, conditioning, upgrading, temporary storage, quality assurance, receiving industries and final management of non-qualifying fractions. Feasible links depend on product stability, contaminant mobility, physical handling characteristics, receiving-process tolerance and the capacity to preserve traceable batch identity. This formulation explains why centralizing a treatment operation may reduce unit processing costs yet increase transport burdens, blending risks or rejection rates, whereas decentralized pretreatment may reduce transported mass but introduce additional energy and reagent demand [38,40,59].

For water, network design must consider the coincidence of quality and demand in time, rather than the gross volume of effluent treated. For metal-bearing concentrates, upgrading requirements and impurity specifications determine whether shipment to a downstream processor is credible. For tailings-derived construction materials, physical durability and contaminant-release behavior should be assessed under exposure conditions relevant to the proposed application, including aging where reported. These examples illustrate a shared principle: the chemistry of the recovered stream defines the admissible set of logistical destinations [21,35,58].

4.3. Industrial Symbiosis Requires a Verified Receiver Interface

A proposed end use does not constitute evidence of an operating industrial symbiosis. A credible exchange must identify a receiving process, the required material specification, the quantity and timing of demand, environmental and regulatory constraints, and a mechanism for accepting or rejecting delivered batches. Where studies demonstrate only laboratory suitability, the finding should be retained as a candidate symbiotic pathway. Where pilot-scale trials or actual delivery records exist, the maturity of the exchange should be reported separately. Such differentiation prevents laboratory

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valorization potential from being conflated with commercially sustained material substitution [23,37,39].

For tailings-derived binders and cementitious materials, receiver qualification must extend beyond compressive strength to address compositional reproducibility, long-term performance and exposure-dependent environmental release. For metal recovery, product purity and the treatment of accompanying residues are central. For reclaimed water, fit-for-process chemistry and reliability of supply are decisive. The resulting recipient-specific qualification requirements should therefore be represented explicitly in future cross-sectoral resource-flow studies rather than appended as generic assumptions [25,34,35,53].

4.4. A Proposed Reporting Architecture for Chain-Level Circularity

The Circular Resource Qualification–Logistics Interface (CRQLI) developed in this review provides a conceptual reporting sequence: (i) define the source and characterize chemical and temporal variability; (ii) quantify the recoverable output and its residual fractions; (iii) specify product-quality and environmental acceptance criteria; (iv) identify feasible storage, transport and upgrading routes; (v) document recipient demand and acceptance; and (vi) compare the full chain with a clearly stated counterfactual. Each step should retain its own evidence status, such that measured operating results, scenario assumptions and conceptual proposals are not presented as equivalent forms of validation [40–42].

At the network scale, reporting should distinguish recovered output at the treatment boundary, qualified output meeting a named specification, delivered output arriving at an identified receiver, and verified output incorporated into production. The framework is intended to improve comparability and reveal where evidence is missing; it is not a mathematically optimized network, a regulatory certification system or a field-validated prediction tool. Its proposed contribution is to make the chemistry–logistics interface explicit and auditable within circular-mining assessments.

5. Limitations of the Evidence Base

5.1. Heterogeneity and Limits of Quantitative Comparability

The 61-record bibliographic corpus encompasses different copper-mining settings, residual streams, experimental scales and analytical purposes. Direct comparisons of recovery rates, environmental impacts, transport requirements or economic outcomes are therefore constrained by differences in feed composition, baseline treatment, system boundary, functional unit and assumed product substitution. Aggregating heterogeneous values into a pooled performance estimate would imply a degree of comparability not established by the present evidence. Accordingly, the synthesis is qualitative and interpretive rather than a meta-analysis or a numerical ranking of network configurations [41,42,59].

5.2. Distinguishing Evidence of Recovery from Evidence of Reintegration

A second limitation concerns the maturity of circularity claims. The presence of resource-recovery experiments, prospective material applications or network-design scenarios does not independently establish sustained industrial uptake. In particular, Vargas et al. [36] supports uncertainty-aware assessment of water circularity rather than verified chain-of-custody, while [21,23,53] provide distinct laboratory evidence for stabilization, limited durability testing and binder formulation, respectively, rather than long-term field certification. In particular, the absence of a reported receiver, acceptance protocol, chain-of-custody record or long-term monitoring should be interpreted as a reporting or verification limitation, not as proof that no such activity occurred. Conversely, a proposed exchange cannot be classified as implemented without corresponding evidence. This distinction is essential when interpreting construction-material valorization, metal recovery and reclaimed-water reuse studies together [21,23,35].

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5.3. Review-Process and Source-Access Constraints

This review was undertaken by a single reviewer, introducing potential selection, extraction and interpretation bias that could not be mitigated through independent duplicate screening or adjudication. The PRISMA sequence reconciles 478 records archived in S0, 373 excluded by the preliminary copper-term rule, 105 screened records, 33 title/abstract exclusions, 72 full texts retrieved and assessed, 11 full-text exclusions and 61 included publications. The author confirms the Scopus expression and reports the search-and-selection interval as 8 June–9 October 2026, but S0–S1 do not preserve an exact query-execution timestamp or pre-archive deduplication count. Restriction to Scopus and the copper-term occurrence filter may have omitted relevant work, especially transferable studies lacking the term in indexed fields. Although the full texts informed qualitative interpretation, S1 provides screening rationales rather than a comprehensive extraction workbook or study-by-study risk-of-bias assessment. No formal publication-bias analysis, certainty-of-evidence grading, or quantitative robustness/sensitivity analysis was performed; the absence of these procedures limits confidence in cross-study generalization and should not be read as evidence that bias is absent. The design-sensitive interpretation instead limits claims to what individual reports document, distinguishes proposed from verified industrial use, and avoids pooled estimates across incompatible designs. These reporting and methodological limitations are acknowledged explicitly rather than retrospectively represented as completed assessments; they do not change the traceable selection counts.

5.4. Boundaries of the Proposed CRQLI Framework

The CRQLI framework has not been calibrated against measured multi-site copper-mining logistics networks or prospectively tested against observed recipient acceptance, storage-induced chemical change and displacement of primary materials. Its applicability may also vary with geography, energy mix, water scarcity, transport infrastructure, waste classification and local regulatory requirements. Accordingly, the framework is best interpreted as a testable integrative hypothesis and a reporting architecture. It does not establish that one particular network arrangement is universally superior or that circular recovery necessarily reduces environmental impacts [38,42,61].

6. Conclusions and Future Outlook

6.1. Principal Conclusions

This systematic review synthesizes 61 publications selected through a reconstructable, but not fully independently auditable, workflow: 478 Scopus records archived in S0; 373 removed through a preliminary copper-term filter; 105 screened; 33 excluded by title/abstract; 72 assessed in full text; and 11 excluded after full-text review. The resulting evidence supports diverse recovery and material-qualification pathways but does not consistently document the downstream conditions needed to establish industrial circularity. In particular, experimental performance, prospective environmental benefits, and proposed recipient pathways must not be conflated with verified delivery and utilization.

The principal gap lies at the chemistry–logistics interface. Feed heterogeneity, contaminant speciation, reclaimed-water quality, storage-related changes, and product durability influence whether a recovered stream can meet a recipient's specification. Transport capacity, temporal demand, traceability, and residual management then determine whether qualified outputs can be delivered and used responsibly. The reviewed evidence seldom reports these conditions together within comparable spatial, temporal, and environmental boundaries.

6.2. Scientific and Methodological Contribution

The Circular Resource Qualification–Logistics Interface (CRQLI) is the principal conceptual contribution. It distinguishes recovery, qualification, delivery, and verified use, and specifies the information and decision gates linking these stages. CRQLI is not a calibrated optimization model or a

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demonstrated industrial network. Its value is to make the assumptions behind circularity claims explicit and to identify measurable outcomes that can be tested in prospective, recipient-linked studies.

6.3. Research Outlook

Future studies should trace identified resource batches from generation to final use across multiple copper-mining contexts. Priority measurements include temporal feed variability, product conformity and stability, recipient demand and acceptance, transport and storage requirements, residual fate, and the energy, cost, and environmental consequences of alternative network configurations. Comparative field studies and uncertainty-aware optimization could then test whether qualification-constrained networks outperform recovery-centered alternatives under clearly defined system boundaries.

In summary, copper-mining circularity should be assessed not solely by the amount of material recovered, but by the quantity of qualified secondary resources demonstrably delivered to and utilized by compatible recipients, with residual burdens accounted for. The proposed framework provides a testable basis for that assessment; operational validation remains a priority.

Supplementary Materials: The following supporting information can be downloaded at the website of this paper posted on Preprints.org, S0 (Scopus bibliographic archive); S1 (screening matrix); PRISMA 2020 checklist.

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Data Availability Statement: Supplementary Table S0 provides the 478-record Scopus bibliographic archive. Supplementary Table S1 records the 105 publications advanced to formal screening, their PRISMA stage and individual narrative justification: 33 title/abstract exclusions, 11 exclusions after full-text assessment and 61 inclusions. The 373 S0 records excluded by the preliminary copper-term filter were not classified as duplicates. The author reports full-text reading of all 72 reports advanced to eligibility assessment. The inclusion rationales in S1 establish selection traceability and the scope of each contribution, whereas the seven methodological domains were considered qualitatively and according to study design; S1 is not a standardized domain-by-domain quality-score dataset. No unrecorded ratings, numerical outcomes or pre-archive duplicate counts are implied. The reported search-and-selection period was 8 June–9 October 2026; a separately timestamped Scopus query log is not included in S0–S1.

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Abbreviations

The following abbreviations are used in this manuscript.

AMD	Acid mine drainage
BMED	Bipolar Membrane Electrodialysis
CO_2	Carbon Dioxide
DOI	Digital Object Identifier
ED	Electrodialysis
FO	Forward Osmosis
GIMA	Research Group on Materials and Environment
IX	Ion Exchange
LCA	Life-Cycle Assessment

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MD	Membrane Distillation
MDC	Membrane Distillation Crystallization
NF	Nanofiltration
OARO	Osmotically Assisted Reverse Osmosis
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
RED	Reverse Electrodialysis
REEs	Rare Earth Elements
RO	Reverse Osmosis
SX	Solvent Extraction
TEA	Techno-Economic Assessment
UTPL	Universidad Técnica Particular de Loja
ZLD	Zero Liquid Discharge
CRQLI	Circular Resource Qualification–Logistics Interface

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