



Parameter-Based Selection of Acid Mine Drainage and Coal Mine Wastewater Treatment: Evidence and Operational Constraints

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SUBMITTED: 3 August 2026; REVISED: 20 September 2026; ACCEPTED: 23 September 2026

ABSTRACT: Acid mine drainage (AMD) and coal mine wastewater differed in acidity, metal loading, sulfate concentrations, suspended solids, and flow characteristics, requiring treatment approaches to be matched to site-specific water quality and operational constraints. This structured desk-based technical review synthesized 64 retained full-text studies using predefined screening criteria, study-level data extraction, and categorical evidence appraisal. Neutralization was found to be most defensible for acidity correction and Fe/Al precipitation but transferred contaminants to sludge and could leave Mn and sulfate unresolved. Passive systems provided potential for long-term treatment where sufficient land and retention time were available, although field evidence demonstrated sensitivity to hydraulic loading, seasonality, substrate condition, and maintenance. Adsorption was better supported as a capacity-limited polishing process than as a universal primary treatment, while electrocoagulation required reliable power, electrode management, and sludge handling and remained weakly represented by full-scale standalone coal-mine applications. The resulting matrix linked wastewater chemistry and mass loading with evidence maturity, land availability, energy and reagent requirements, maintenance needs, and residual-management constraints to screen single-stage or combined treatment trains. Membrane processes, biological sulfate reduction, and resource-recovery options were considered complementary treatment stages where their operational requirements matched the treatment objectives. Site characterization, pilot-scale verification, residual assessment, life-cycle cost analysis, and confirmation of applicable discharge requirements remained necessary before final treatment design.

KEYWORDS: Evidence transferability; manganese control; sulfate persistence; residual management; treatment train selection

1. Introduction

Acid mine drainage (AMD) was a persistent water-quality problem in sulfide-bearing mining environments, including coal-mining areas. AMD and coal mine wastewater differed among sites and required engineered control based on their chemical characteristics and flow conditions [1, 2]. Without adequate treatment, acidic and metal-rich water could degrade receiving waters, sediments, and surrounding soils [3, 4]. Coal mine wastewater management could not be based on pH alone. Treatment feasibility also depended on acidity, metal mobility,

sulfate concentrations, suspended solids, sludge generation, flow variability, land availability, access to power and reagents, and local maintenance capacity [2, 5, 6]. A process that performed well for one wastewater composition could be ineffective or impractical at another site.

AMD and mine-water treatment options included alkaline neutralization, adsorption/sorption, passive and biological systems, electrochemical treatment, membrane separation, hybrid treatment, and resource-recovery processes [1, 7, 8]. The detailed comparison retained neutralization, adsorption, passive/biological treatment, and electrochemical treatment as the main process groups because they represented distinct treatment mechanisms and operational requirements. Membrane, hybrid, and resource-recovery options were assessed as complementary or emerging treatment stages where the retained evidence supported their application. Treatment evidence was fragmented across wastewater matrices, pollutant targets, operating conditions, and experimental scales. Synthetic/model-water and short-term batch studies could establish mechanisms or demonstrate feasibility, but they did not provide the same level of confidence for field transfer as pilot- or full-scale studies using actual mine water. The review therefore interpreted treatment performance together with the water basis, study scale, operational realism, and completeness of reporting rather than comparing removal percentages in isolation [8–10].

Existing AMD reviews synthesized treatment mechanisms, sustainability considerations, hybrid treatment approaches, and resource-recovery opportunities [7–11]. The present review advanced this literature by linking four elements within a single decision-making structure: measured wastewater chemistry and mass loading, study-level evidence maturity and transferability, site and operational constraints, and residual-management consequences. The resulting matrix was not intended as a universal technology ranking or a validated design model; rather, it provided an evidence-bounded screening framework that explained when a single process was sufficient, when a treatment train was justified, and the extent to which laboratory, non-coal, pilot-scale, and field evidence could be transferred to coal mine wastewater applications.

2. Materials and Methods

2.1. Review design and scope.

The review compared treatment mechanisms, pollutant targets, operational requirements, residuals, and site-specific constraints associated with AMD and coal mine wastewater. It covered pollution control, environmental risks, sludge and secondary-waste management, and treatment selection while excluding mine planning, ore genesis, production optimisation, and project valuation. The detailed comparison focused on neutralisation and precipitation, adsorption/sorption, passive ecological and biogeochemical treatment, and electrochemical treatment, with electrocoagulation considered the principal active process. These treatment groups were selected because they represented distinct primary or polishing functions. Membrane separation, biological sulfate reduction, and resource-recovery processes were evaluated as complementary or emerging stages where the retained evidence addressed persistent sulfate or salinity, water-reuse objectives, or the recovery of treatment residuals and dissolved metals. These options were not ranked as universal substitutes for the core treatment

groups; instead, their roles were assessed within the context of treatment-train requirements and evidence transferability.

2.2. Literature Search Strategy.

The formal literature search was conducted using ScienceDirect Advanced Search, with searches performed in the “Title, abstract or author-specified keywords” field and restricted to publications from 2014 to 2026. The results were sorted by relevance. Twenty-four formal search sets (SD01A–SD07D2) were conducted, yielding 4,546 canonical retrieval occurrences before record-level deduplication. The complete Boolean search strings and raw-hit counts for all 24 searches were provided in the Supplementary Materials. Google Scholar was used as a concordance check rather than as a second independently pooled formal database. The exact query “acid mine drainage” treatment “coal mine” was restricted to publications from 2014 to 2026 and sorted by relevance. The first 50 results were screened after patents and citation-only records had been excluded; no additional unique records were identified after comparison with the ScienceDirect evidence base.

The formal ScienceDirect search architecture was cluster-based and was preserved by search identifier: neutralisation (SD01A–SD01B2), adsorption (SD02A–SD02B2), passive/wetland and sulfate-reducing processes (SD03A–SD03B2), electrocoagulation (SD04A–SD04B), manganese and sulfate control (SD05A–SD05D2), residual/sludge management (SD06A–SD06B), and membrane separation, resource recovery, hybrid treatment, cost/energy, and field operation or scale-up (SD07A–SD07D2). The exact Boolean strings and raw-hit counts for each formal search were provided in the Supplementary Materials. Supplementary sensitivity searches (OS01–OS08) were recorded separately to evaluate terminology, source coverage, coal-specific evidence, residuals, passive/biological treatment, electrocoagulation, resource recovery, and Indonesian coal-mine evidence. These searches were not included in the formal ScienceDirect raw-hit denominator.

The initial literature search was conducted from 4 to 6 July 2026. The search was subsequently updated through documented supplementary sensitivity searches on 26 August 2026 and a Google Scholar concordance check on 28 August 2026. Retrieval substitutions and source-provenance records were provided in the Supplementary Materials. Eligible evidence included primary laboratory, pilot/continuous, and field/full-scale mine-water studies, together with reviews, technical guidance, and applicable regulatory materials used to provide supporting context. Qualitative comparative synthesis was employed because wastewater composition, treatment configuration, study scale, duration, and reported endpoints were too heterogeneous to permit pooled performance estimation.

2.3. Source Selection and Screening Logic.

Before record-level deduplication, duplicate RIS exports and incorrectly assigned duplicate files were removed to ensure that each formal search contributed only its canonical retrieval records. DOI strings were converted to lowercase, and DOI URL and prefix variants were removed. Exact normalised DOI matching was used as the primary deduplication criterion. Exact normalised title matching was subsequently used as a safeguard after Unicode normalisation, lowercasing, punctuation removal, and whitespace collapse. Fuzzy-title matching was not applied. These procedures reduced the 4,546 canonical ScienceDirect retrieval occurrences to 1,691 unique records.

Title and abstract screening initially retained 537 records and excluded 1,154 records. A secondary verification subset of 112 records initially excluded under E2/E3 was reassessed, resulting in the reinstatement of 84 records. One additional record was subsequently confirmed following source verification. The final ScienceDirect evidence-review pool therefore comprised 622 records. Supplementary searching identified 37 external or legacy records, including 31 new main-window records, two duplicates of ScienceDirect records, two exclusions, and two legacy/supportive records. The combined main-window evidence-review pool therefore comprised 653 records. A coverage-based evidence-priority set of 67 records was selected for intensive full-text extraction. The final disposition comprised 64 retained studies, two full-text exclusions, and one record that could not be retrieved. Twelve documented retrieval substitutions were used when originally selected priority records were inaccessible. These substitutions were non-additive and did not alter the 67-record evidence-priority set or its final disposition. The complete selection process is illustrated in Figure 1 and summarised numerically in Table 1.

Table 1. Literature identification, screening, and full-text disposition.

Stage	Count	Interpretation
Formal ScienceDirect search sets	24	SD01A-SD07D2; exact Boolean strings and raw hits are provided in the Supplementary Materials.
ScienceDirect canonical retrieval occurrences	4,546	Sum of the 24 formal search-set raw hits before record-level deduplication.
Unique ScienceDirect records	1,691	Exact normalized DOI matching, with exact normalized title as safeguard; fuzzy-title matching was not used.
Initial title/abstract inclusions	537	Advanced after initial screening.
Initial title/abstract exclusions	1,154	Excluded at initial screening.
Secondary verification subset	112	Initially excluded E2/E3 records selected for reassessment.
Records reinstated after secondary verification	84	Eligibility confirmed after reassessment.
Additional eligibility verification	1	Treatment relevance confirmed after source verification.
Final ScienceDirect evidence-review pool	622	$537 + 84 + 1$.
External or legacy records logged	37	Maintained under separate provenance.
New external main-window records	31	Added to the main-window evidence-review pool.
External duplicates to ScienceDirect	2	Not counted twice.
External exclusions	2	Did not advance.
Legacy/supportive records	2	Outside the main 2014-2026 count.
Combined main-window evidence-review pool	653	622 ScienceDirect + 31 new external main-window records.
Evidence-priority set	67	Coverage-based set selected for intensive full-text extraction.
Retained full texts	64	Final study-level evidence database.
Excluded full texts	2	Excluded after full-text assessment.
Not retrieved	1	Reported separately from scientific exclusion.

2.4. Summary of the Retained Evidence Base.

Figure 1 illustrates the complete literature identification and screening process, including database retrieval, deduplication, title and abstract screening, evidence-review pooling, evidence-priority selection, and final full-text disposition. The formal ScienceDirect search generated 4,546 canonical retrieval occurrences from 24 search sets. After DOI- and title-based deduplication, 1,691 unique records underwent title and abstract screening. Following secondary verification, 622 ScienceDirect records were retained in the evidence-review pool. The addition of 31 new external main-window records increased the combined pool to 653 records. From these, 67 records were selected for intensive full-text evaluation, resulting in 64 retained full texts, two full-text exclusions, and one record that could not be retrieved (Figure 1).

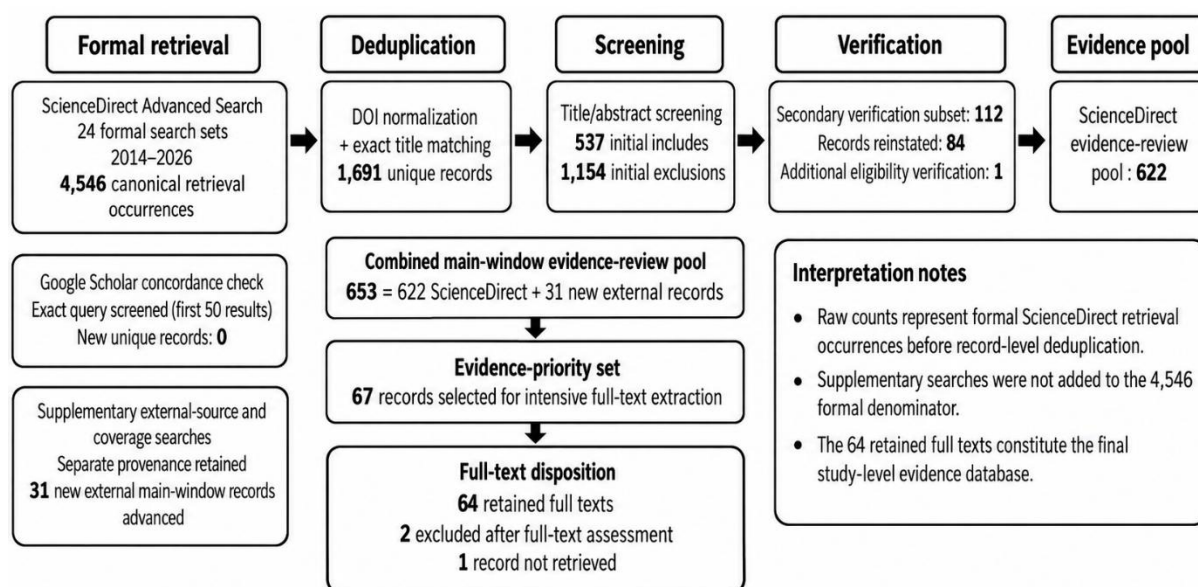


Figure 1. Literature search, screening, and full-text selection workflow.

Table 1 provides the corresponding numerical summary of the literature identification and study-selection process. It distinguishes the 4,546 initial retrieval occurrences from the 1,691 unique ScienceDirect records, the 622-record final ScienceDirect evidence-review pool, the 653-record combined main-window evidence-review pool, the 67-record intensive evidence-priority set, and the 64 full-text studies ultimately retained in the study-level evidence database. This distinction provided a transparent account of how the initial literature pool was progressively reduced to the final evidence base used for comparative synthesis (Table 1).

2.5. Evidence Extraction.

For each retained full-text study, data were extracted on the mine and wastewater context, geographical location, water basis, treatment train, study scale, batch or continuous operation, influent characteristics, operating conditions, treatment performance, target pollutants, residual generation and handling, cost and energy information where reported, maintenance and scale-up constraints, resource-recovery information, transferability to coal mine wastewater, and author-reported limitations. Numerical values were retained as originally reported and were not normalised into universal design values when study conditions were not comparable. The complete study-level extraction and evidence appraisal for all 64 retained studies, together with the full-text disposition of all 67 evidence-priority records, were provided in the Supplementary Materials. Detailed search, screening, retrieval, source-provenance, and study-selection records were also provided therein.

2.6. Evidence Appraisal.

Each retained full-text study was appraised using four predefined categorical dimensions. Relevance (R) distinguished actual coal AMD or coal mine wastewater (R1), actual non-coal or unspecified mine water (R2), synthetic/model water (R3), and review/guidance evidence (R4). Study scale (S) distinguished field/full-scale studies (S1), pilot or continuous-flow studies (S2), laboratory/batch studies (S3), and secondary evidence for which scale was not applicable (S4). Operational realism (O) distinguished long-term, continuous, field, or seasonal evidence (O1); short-duration but operationally explicit evidence (O2); optimised short-batch

evidence (O3); and secondary evidence (O4). Reporting completeness (C) distinguished higher completeness (C1), useful but incomplete reporting (C2), and low completeness (C3).

No additive numerical score or post hoc performance threshold was applied. The overall evidence class was assigned according to predefined categorical rules: Strong for direct evidence with strong contextual fit and operationally meaningful field or pilot information; Moderate for direct evidence with scale or transferability limitations or strong actual non-coal mine-water evidence; Limited for synthetic, batch, material-specific, or otherwise limited-transferability evidence; and Supportive for reviews, guidance, or other secondary evidence. The resulting evidence base comprised nine Strong, 30 Moderate, eight Limited, and 17 Supportive studies. These counts were reported descriptively and were not used to redefine the classification rules. Complete study-level codes and evidence-class assignments were provided in the Supplementary Materials.

2.7. Comparative Synthesis and Matrix Development.

The comparative synthesis followed a parameter-first rather than a technology-ranking approach. For each treatment group, findings were compared according to influent pH and acidity; Fe, Mn, Al, sulfate, and TSS loading; flow and hydraulic conditions; dose or media loading; contact time or hydraulic retention time; current density and electrode configuration, where applicable; residual generation; maintenance requirements; and study scale. Evidence relevance and transferability were considered before treatment-performance values were used to develop the treatment-selection matrix.

Treatment trains were developed when the retained evidence indicated that a single process addressed a dominant pollutant load but left a documented residual or operational constraint, such as Mn or sulfate after acidity correction, TSS before an active polishing stage, or sludge and spent media following contaminant removal. Cost and energy requirements were treated as qualitative screening criteria unless individual studies reported explicit values under clearly defined conditions. Because the retained studies did not provide comparable life-cycle cost, footprint, or energy data across technologies, no cross-technology economic ranking was performed. The retained studies were grouped according to their primary analytical clusters in Table 3 to structure the comparative synthesis, although cross-cutting studies could contribute evidence to more than one analytical theme.

3. Results and Discussion

The synthesis was based on 64 retained full-text studies. The evidence base comprised 34 R1 records involving actual coal AMD or coal mine wastewater, 10 R2 records involving actual non-coal or unspecified mine water, three R3 records involving synthetic/model water, and 17 R4 review/guidance records. By study scale, the database contained eight S1 field/full-scale studies, 22 S2 pilot or continuous-flow studies, 15 S3 laboratory/batch studies, and 19 S4 secondary-evidence records. The overall evidence classes comprised nine Strong, 30 Moderate, eight Limited, and 17 Supportive studies. Detailed study-level extraction, evidence appraisal, transferability assessment, and supporting search and screening records were provided in the Supplementary Materials.

3.1. Source-to-Treatment Logic of AMD and Coal Mine Wastewater.

Treatment screening began with wastewater characterisation rather than technology preference. The dominant treatment objectives were determined by pH, acidity, Fe, Mn, Al, sulfate, TSS, flow, mass loading, and seasonal variability, whereas implementation feasibility depended on land availability, power supply, reagent access, operator capacity, and residual-handling requirements. The relationship between these parameters and treatment selection was further incorporated into Table 2.

Table 2. Key AMD and coal mine wastewater parameters for treatment selection.

Parameter	Why it matters	Risk implication	Monitoring relevance	Treatment implication	Ref.
pH	Controls metal solubility and reagent demand	Acidifies water and soil; mobilizes metals	Common regulated marker; first screening test	Drives neutralization, precipitation, adsorption pH dependence	[1–3, 5]
Acidity	Sets alkalinity demand for correction	Consumes buffering capacity; sizes reagent load	Design driver rather than routine limit	Sets neutralization demand and passive-system loading	[2, 3, 5]
Iron (Fe)	Often the dominant metal with Al	Forms hydroxide solids and sludge; armors limestone	Common regulated marker; sludge indicator	pH correction, precipitation, settling, adsorption, EC	[1–3,5]
Manganese (Mn)	More persistent than Fe or Al	Residual after basic neutralization	Common regulated marker; polishing indicator	Often needs higher pH, oxidation, adsorption, or EC	[2, 3, 5]
Aluminum (Al)	Common under acidic conditions	Precipitates as hydroxide; sludge and clogging	Tracks precipitation and armoring	Relevant to neutralization and solids control	[1–3, 5]
Sulfate	Common in sulfide-derived drainage; concentration is site-dependent	Increases dissolved-solids loading and can promote secondary mineral formation	Design driver; not always a routine limit	Not resolved by neutralization; may need SRB or membranes	[2, 9–11]
TSS	Variable; may be high in coal mine wastewater	Turbidity, sedimentation, metal-bearing flocs	Common regulated marker	Settling, filtration, EC; may need pre-settling	[3, 6, 8]
Treatment residuals / sludge	Generated during treatment	Concentrate metals and may require stabilization or disposal	Quantity, composition, and stability monitored during operation	Affect dewatering, reuse, disposal, land, cost, and process feasibility	[1, 2, 9–11]

Note: Abbreviations: EC, electrocoagulation; SRB, sulfate-reducing bacteria; TSS, total suspended solids.

3.2. Key Parameters and Environmental Risks Driving Treatment Selection

The reviewed cases ranged from strongly acidic to near-neutral waters, demonstrating that treatment requirements could not be inferred from pH alone. Important parameters included acidity, Fe, Mn, Al, sulfate, TSS, and treatment residuals because these variables influenced environmental risks, monitoring requirements, and the selection of appropriate treatment processes. Table 3 summarised the principal AMD and coal mine wastewater parameters and linked each parameter to its environmental significance, monitoring relevance, and treatment implications.

Table 3. Comparison of AMD and Coal Mine Wastewater Treatment Technologies.

Primary synthesis cluster	Dominant treatment role	Performance drivers	Field-transfer constraints	Residual / operational burden	Interpretation	Retained evidence
Neutralization / precipitation / co-treatment	Acidity correction, Fe/Al precipitation, solids conditioning, selective precipitation, or co-treatment.	Influent acidity and buffering demand; reagent reactivity and dose; target pH; Fe/Mn/Al interactions; mixing, aeration, settling, and flow.	Mn and sulfate may persist after pH correction; field behavior depends on loading, sludge recirculation/settling, hydraulic control, and reagent logistics.	Metal-hydroxide/gypsum-rich sludge, reagent demand, dewatering/stability, or additional polishing.	Best treated as a primary conditioning stage when acidity or precipitable metals dominate, not as a universal complete treatment.	[15–29]
Adsorption / sorption	Polishing of residual dissolved metals or selected contaminants after primary treatment.	Influent pH and competing ions; media chemistry and dose; contact time; cumulative loading; breakthrough and regeneration behavior.	Most retained evidence is material-specific or limited in duration; batch removal percentages do not establish field media life.	Spent media, regeneration/replacement, leaching risk, and disposal or reuse.	Use as capacity-limited polishing unless continuous breakthrough and residual-management performance are demonstrated.	[30–33]
Passive / biological / sulfate-reducing systems	Low-energy attenuation, Fe removal, acidity control, sulfate reduction, or staged passive treatment.	Hydraulic and mass loading; HRT; temperature; redox; substrate/carbon availability; vegetation/media condition; seasonality.	Long-term performance can change with flow, temperature, clogging, ochre accumulation, substrate aging, redox shifts, and maintenance.	Land demand, long HRT, sediment/ochre accumulation, substrate renewal, sulfide/organic residuals.	Most defensible where land and retention time are available and seasonal loading can be managed.	[34–50]
Electrochemical / bioelectrochemical	Active solids/metal removal, electrocoagulation polishing, sulfate-related combined treatment, or bioelectrochemical treatment.	Current density, electrode material/configuration, spacing, pH, treatment time, conductivity, influent load, and solids separation.	Bench and pilot results require qualification for power reliability, passivation/fouling, electrode consumption, sludge handling, and operator control.	Electricity, electrode consumption, sludge, cleaning/passivation control, and instrumentation.	Use where active operation is feasible; do not assume electrochemical treatment alone resolves dominant acidity or sulfate.	[51–55]
Membrane / resource recovery / hybrid emerging systems	Dissolved-salt control, water reuse, resource recovery, hybrid treatment trains, or recovery of metals/REEs.	Pretreatment, fouling/scaling, pressure or osmotic gradient, water recovery, feed concentration, selectivity, product purity, and market/off-take conditions.	Pilot and non-coal evidence can support feasibility, but concentrate management, scale-up, energy, economics, and long-term reliability remain site-specific.	Brine/reject, chemical demand, additional unit operations, monitoring, product-quality control, and capital/energy burden.	Complementary stages are justified when a documented residual or reuse/recovery objective remains after primary treatment.	[56–70]

Note: Reference ranges identify retained studies assigned to each primary analytical cluster. Cross-cutting studies may inform more than one analytical theme, while review/framework studies used for overarching context are cited in the Introduction.

3.3. Monitoring Parameters and Treatment Implications.

Ministerial Decree No. 113/2003 specified reference values of pH 6–9, Fe at 7 mg L^{−1}, Mn at 4 mg L^{−1}, and TSS at 400 mg L^{−1} for coal-mining effluent [12], while Government Regulation No. 22/2021 provided the broader environmental-management framework [13]. Applicable

provincial and permit-specific requirements still needed to be confirmed for individual sites. Although acidity and sulfate might not have been routine discharge parameters, they remained important design variables because they affected reagent demand and treatment-train configuration. Sujiman [14] reported near-neutral open-pit coal mine wastewater with variable and occasionally high TSS, demonstrating that an acceptable pH did not eliminate the need for solids control.

3.4. Comparative Review of Treatment Technologies.

Treatment technologies were compared according to their dominant roles, performance drivers, field-transfer constraints, residual burdens, and appropriate interpretations rather than isolated maximum removal efficiencies. Evidence was not pooled across different water bases or study scales. R1 evidence from actual coal AMD or coal mine wastewater provided the highest direct transferability. R2 evidence from actual non-coal mine water was considered where wastewater chemistry and operational mechanisms were comparable. R3 synthetic/model-water evidence was used only to support mechanisms or feasibility, whereas R4 review/guidance evidence provided supporting rather than direct performance evidence. Reported treatment efficiencies were therefore interpreted in relation to influent pH and acidity; Fe, Mn, Al, sulfate, and TSS loading; reagent or media dose; contact time or HRT; electrode or membrane conditions; flow regime; study duration; and scale. Scale-up could have altered apparent treatment performance because of hydraulic variability, competing ions, suspended solids, seasonal temperature and rainfall, media or substrate ageing, electrode or membrane fouling, maintenance frequency, and residual accumulation. Table 3 compared the major treatment groups and demonstrated the differences in their treatment roles, performance drivers, field-transfer constraints, and residual or operational burdens.

3.4.1. Limestone or Alkaline Neutralisation.

Across the retained neutralisation and precipitation studies, treatment performance was governed by acidity loading, buffering demand, target pH, reagent reactivity, mixing and aeration, settling, and residual handling rather than by pH correction alone [15–29]. Direct coal-mine field and pilot studies demonstrated that alkaline treatment could correct acidity and effectively remove Fe and Al under appropriate dosing conditions. However, Mn commonly required a different pH or oxidation window, while sulfate was not reliably removed by conventional neutralisation. Selective precipitation and co-treatment studies further demonstrated that changes in pH, reagent type, or mixing ratio affected both contaminant removal and the composition or quantity of the resulting residual stream. High-density-sludge and resource-recovery studies reinforced the same trade-off because dissolved contaminants were transferred into solids that required characterisation, dewatering, stabilisation, reuse, or disposal. Neutralisation was therefore most appropriately interpreted as a primary conditioning stage, with Mn-, sulfate-, solids-, or residual-specific treatment added when these constraints remained after clarification.

3.4.2. Adsorption-Based Treatment.

Adsorption and sorption were most appropriately interpreted as capacity-limited polishing processes. Across the retained adsorption studies, apparent performance varied according to influent pH, competing ions, media chemistry and dosage, contact time, cumulative loading,

and whether the experiment measured initial batch removal or continuous breakthrough [30–33]. Consequently, high short-duration removal efficiencies were poor substitutes for field-scale media-life data. For treatment selection, important considerations included whether acidity or suspended solids required upstream control, whether the available contact time and bed volume were sufficient, how rapidly adsorption capacity was exhausted under site-specific loading, and whether spent media could be regenerated, stabilised, reused, or safely disposed of. Until stronger continuous coal-mine data became available for breakthrough, regeneration, leaching, and cost, adsorption was more defensible as a targeted polishing process than as a universal primary treatment.

3.4.3. Constructed Wetlands and Passive Treatment.

Passive and biological treatment provided particularly clear evidence that short-term removal efficiency and long-term field reliability were not equivalent. Across the retained field, pilot, and review evidence, treatment performance depended on hydraulic and mass loading, HRT, temperature, redox conditions, substrate or carbon availability, vegetation and media condition, seasonality, and the accumulation of ochre or other reactive solids [34–50]. Long-term coal-mine treatment systems demonstrated that Fe removal could remain high while varying considerably with season and unit geometry. Sulfate-reducing systems could decline in performance as temperature, redox conditions, substrate quality, or HRT changed. Passive treatment media could also retain metals effectively while still requiring management of clogging, sediment accumulation, substrate ageing, and residual stability. Passive or biological treatment was therefore most defensible where sufficient land and retention time were available and where seasonal loading, maintenance access, and residual stability could be monitored throughout the operational life of the system rather than inferred from a single removal percentage.

3.4.4. Electrocoagulation.

Electrochemical and bioelectrochemical performance depended on influent loading and pH, together with current density or electrochemical configuration, electrode material and spacing, treatment time, conductivity, and downstream solids separation [51–55]. The retained evidence included coal-specific bioelectrochemical systems, electrocoagulation under controlled conditions, and combined precipitation–electrocoagulation treatment. The evidence supported mechanism selection and operational optimisation, but scale-up remained constrained by electrical demand, electrode consumption, passivation and fouling, hydraulic control, sludge separation, and operator capacity. Electrochemical treatment was therefore most defensible as an actively controlled solids-removal, metal-removal, or polishing stage where reliable power and maintenance were available. Dominant acidity or sulfate required appropriate upstream or dedicated treatment rather than being assumed to be adequately addressed by electrocoagulation alone.

3.4.5. Complementary and Emerging Treatment Options.

Complementary and emerging treatment options were most useful when a clearly defined treatment objective remained after primary acidity and solids control. The retained evidence covered coal-mine and non-coal membrane treatment, co-treatment and other hybrid systems, selective precipitation and membrane-assisted recovery, rare-earth and critical-mineral

recovery, and techno-economic or resource-utilisation assessments [56–70]. Membrane studies demonstrated the feasibility of dissolved-salt control and water recovery but also identified pretreatment requirements, fouling and scaling, pressure or osmotic-gradient requirements, energy demand, and brine or reject management as persistent constraints. Resource-recovery studies demonstrated that metals or rare earth elements could be concentrated or recovered from selected mine waters; however, process complexity, selectivity, product purity, reagent demand, and economic feasibility remained strongly dependent on feed characteristics. Hybridisation was therefore justified when a documented residual, reuse, or recovery objective existed rather than on the assumption that additional unit operations would automatically improve treatment performance.

3.5. Evidence Strength and Technology Positioning.

The predefined R/S/O/C appraisal framework was used to determine how strongly individual studies could support technology selection. Strong and Moderate evidence supported treatment screening when wastewater chemistry and operating conditions were sufficiently comparable, whereas Limited evidence was used primarily to support mechanisms or testable design hypotheses. Supportive evidence was used mainly for background and contextual interpretation. Consequently, a high removal efficiency reported in an R3/S3/O3 batch study was not considered equivalent to long-term R1/S1/O1 coal-mine evidence. Table 4 summarised the evidence-appraisal categories, predefined assignment criteria, permitted interpretation, and observed number of studies within each category.

Table 4. Evidence appraisal categories used in the review.

Category	Predefined assignment rule	Interpretation and permitted use	Observed n
Strong	Direct evidence with strong contextual fit and operationally meaningful field or pilot information.	Highest weight for technology comparison when wastewater chemistry and operating conditions are comparable; not a universal performance guarantee.	9
Moderate	Direct evidence with scale or transferability limitations, or strong actual non-coal mine-water evidence.	Supports option screening, design hypotheses, and pilot prioritization; field transfer requires qualification.	30
Limited	Synthetic, batch, material-specific, or otherwise limited-transferability evidence.	Supports mechanism and feasibility only; not used as direct field-performance prediction.	8
Supportive	Review, guidance, or other secondary supportive evidence.	Background, taxonomy, mechanism framing, regulatory or comparative context; not direct treatment-performance evidence.	17

Note: Each retained full text is coded separately for relevance (R1-R4), study scale (S1-S4), operational realism (O1-O4), and reporting completeness (C1-C3). No additive numerical score was used. The observed distribution reflects application of the predefined rules to the 64 retained full texts.

3.6. Technology Selection Framework for AMD and Coal Mine Wastewater.

The parameter-based treatment-selection pathway began with measured wastewater flow, seasonal variability, pH and acidity, Fe, Mn, Al, sulfate, TSS, and associated mass loading. Evidence relevance was then assessed before reported treatment performance was transferred to the site. A single process was retained only when it addressed the dominant pollutant load without generating an unmanaged residual or leaving another parameter above the treatment objective. When a documented residual remained, the framework progressed towards a combined treatment train. Examples included neutralisation followed by settling and Mn or sulfate polishing, pre-settling before an active solids-removal stage, and pretreatment before

membrane or biological treatment. Final treatment selection remained conditional on site constraints, residual management, pilot verification, and operational feedback. Figure 2 illustrates the parameter-based treatment-selection pathway from wastewater characterisation and evidence appraisal to technology screening, treatment-train selection, pilot verification, and operational feedback.

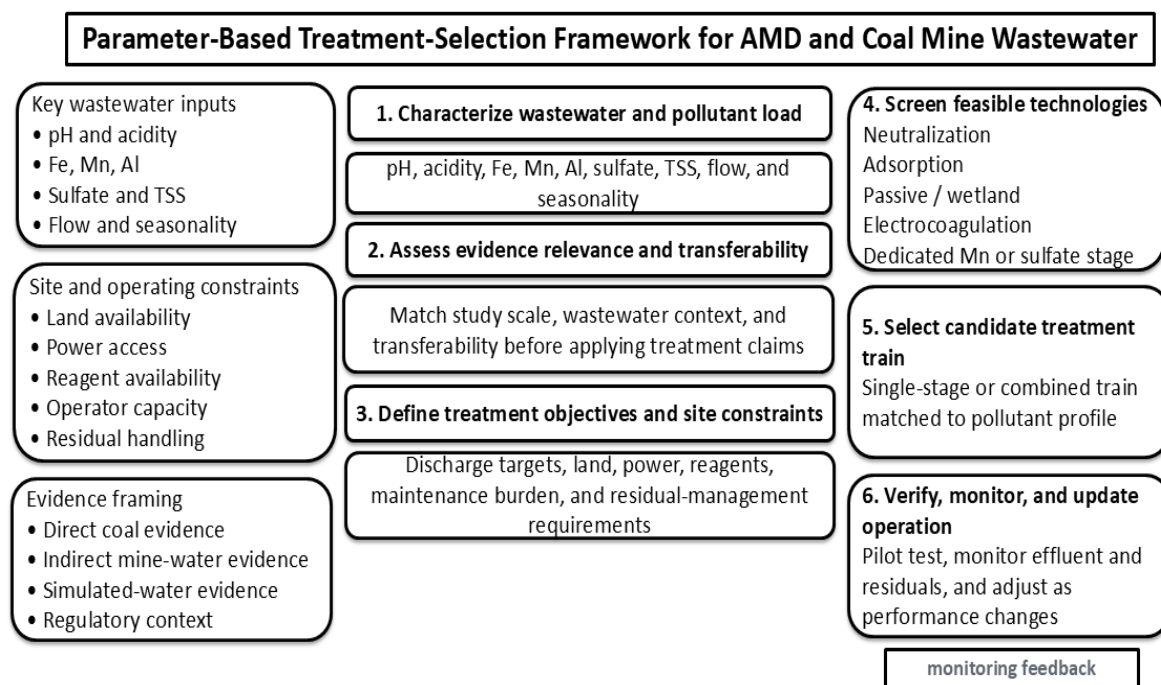


Figure 2. Parameter-Based Treatment-Selection Framework for AMD and Coal Mine Wastewater.

The parameter-based decision framework was subsequently translated into practical treatment sequences according to dominant wastewater conditions and site constraints. Table 5 presents the corresponding treatment-selection matrix, including candidate treatment sequences, reasons for combining processes, critical site checks, and the strength and applicability of the supporting evidence. The treatment trains presented in Table 5 were derived from complementary failure modes rather than from a fixed hierarchy of technologies. Neutralisation–settling–polishing was justified when acidity and Fe/Al were controlled but Mn, sulfate, residual solids, or sludge-management constraints remained [15–29]. Pre-settling before an active solids-removal stage was justified where TSS would otherwise have increased coagulant or electrode demand or burdened downstream polishing [28, 51–55]. High sulfate concentrations required a distinct removal mechanism. The retained passive/SRB evidence, including coal-specific studies, supported biological sulfate reduction where donor supply, redox conditions, temperature, and HRT could be maintained [34–50]. Membrane processes became relevant where dissolved-salt control or water recovery was an explicit treatment objective [56, 57, 59, 70]. Combined treatment was therefore preferred only when a single stage left a documented contaminant, residual, reuse, or operational gap that was relevant to the site-specific treatment objective. Hybridisation was not interpreted as inherently superior. Combined AMD treatment could broaden contaminant removal by sequencing complementary mechanisms, but it could also increase infrastructure requirements, monitoring and maintenance demands, energy or reagent consumption, and the number of residual streams requiring management [9, 10].

Table 5. Parameter-Based Treatment-Selection Matrix for AMD and Coal Mine.

Dominant condition / constraint	Candidate treatment sequence	Rationale and critical checks	Ref.
Very low pH / high acidity; Fe–Al loading	Neutralization → solids separation → polishing	Removes acidity and Fe/Al but may leave Mn/sulfate. Check acidity, target pH, reagent dose, and sludge.	[15–29]
Persistent Mn after neutralization	Higher-pH/oxidative step → sorption or biological polishing	Mn may remain soluble. Check Mn level, pH, competing metals, contact time, and residuals.	[18, 21, 27, 42]
High sulfate	Acidity correction → biological or membrane treatment	Neutralization does not reliably remove sulfate. Check sulfate load, redox, HRT, temperature, and reject.	[35–50, 53, 56, 57]
High TSS / near-neutral wastewater	Pre-settling → coagulation/EC → polishing	Solids may dominate treatment needs. Check TSS load, settling, EC conditions, sludge, and power.	[28, 51–55]
Low-to-moderate flow; sufficient land	Settling → wetland/passive treatment	Suitable for low-energy treatment. Check HRT, loading, seasonality, clogging, and substrate condition.	[34–50]
Residual metals after primary treatment	Fixed-bed sorption/media polishing	Suitable for residual metals. Check pH, breakthrough, media life, and spent-media handling.	[30–33]
High salinity / water reuse	Pretreatment → NF/FO/RO	Targets dissolved salts and sulfate. Check fouling, pressure, energy, recovery, and reject management.	[56, 57]
Resource-recovery opportunity	Selective precipitation or integrated recovery	Recovery depends on feed quality and economics. Check concentration, selectivity, purity, reagents, and residuals.	[19, 23, 61, 62, 64, 66–69]
Limited footprint; reliable power	Pretreatment → electrochemical/membrane treatment	Compact but energy- and maintenance-intensive. Check power, fouling, maintenance, and residuals.	[51–57, 59, 70]

Note: EC, electrocoagulation; FO, forward osmosis; HRT, hydraulic retention time; NF, nanofiltration; REE, rare earth elements; RO, reverse osmosis; SRB, sulfate-reducing bacteria; TSS, total suspended solids.

3.7. Cost, Energy, Residuals, and Operational Considerations.

Comparable life-cycle cost and energy data were not available across the retained technologies; therefore, the framework did not rank treatment options economically. Nevertheless, the evidence supported a qualitative comparison of the major cost and energy drivers. Active neutralisation was influenced by reagent supply, mixing requirements, sludge production, dewatering, and disposal. Adsorption combined relatively simple operation with finite media capacity, regeneration or replacement requirements, and spent-media management. Passive systems minimised external energy demand but required sufficient land, long HRTs, periodic sediment or media maintenance, and tolerance of seasonal performance variations. Electrochemical systems required electricity, electrode replacement, passivation control, and sludge separation [51–55], whereas membrane systems required pretreatment, pumping or pressure, fouling control, and concentrate management [56, 57, 59, 70]. A laboratory precipitation–electrocoagulation study reported an energy consumption of 0.14–0.18 kWh L^{−1} for the electrocoagulation step under the tested conditions [53]. Integrated recovery studies further demonstrated that reagent consumption, product recovery, residual handling, and plant configuration could substantially influence techno-economic performance [66, 67]. These values were therefore treated as condition-specific evidence rather than transferable full-scale cost benchmarks. Site-specific life-cycle costing remained necessary before economic selection.

3.8. Implications for Indonesian Coal Mine Wastewater Management.

For Indonesian coal mines, treatment selection needed to begin with seasonal characterisation of pH, acidity, Fe, Mn, sulfate, TSS, flow, and mass loading because the retained evidence included both acidity-dominated and near-neutral, solids-dominated coal mine waters. Direct Indonesian coal-mine evidence supported quicklime neutralisation under defined operating conditions [29], treatment of coal mine acid water using an NF270 membrane under controlled conditions [70], and co-treatment of AMD with high-TSS coal mine wastewater at a selected mixing ratio [28]. However, these studies remained site- and condition-specific and did not establish universal treatment performance, cost, or reliability for Indonesian coal mines. Full-scale and long-term coal-mine evidence from other regions demonstrated that seasonal flow, temperature, HRT, media condition, residual accumulation, and maintenance could materially affect treatment performance [35, 40, 44, 46]. Such evidence was transferable primarily as an implementation consideration rather than as direct evidence of Indonesian treatment outcomes. Practical treatment design therefore needed to incorporate wet- and dry-season loading assessments, reagent and replacement-media logistics, operator and laboratory capacity, sludge, spent-media, or brine storage, electrode or membrane maintenance where active systems were employed, power reliability, staged pilot or commissioning verification, and confirmation of applicable permit requirements [12–14].

3.9. Limitations of the Evidence Base and Future Research.

The final evidence synthesis comprised 64 retained full-text studies, but substantial heterogeneity remained in wastewater basis, study scale, duration, and reporting completeness. The database contained 34 R1, 10 R2, three R3, and 17 R4 records. However, only eight studies represented S1 field/full-scale evidence, compared with 22 S2 pilot or continuous-flow studies, 15 S3 laboratory/batch studies, and 19 S4 secondary-evidence records. Consequently, only nine studies were classified as Strong, compared with 30 Moderate, eight Limited, and 17 Supportive studies. Adsorption evidence remained dominated by capacity- and material-specific studies, while electrochemical treatment lacked strong standalone full-scale coal-mine evidence. Passive and SRB treatment performance remained sensitive to seasonal flow, temperature, HRT, substrate evolution, redox stability, and maintenance. Comparable full-scale evidence was also limited for life-cycle cost, energy consumption, treatment footprint, sludge stability, spent-media regeneration, brine management, continuous operation, and long-term performance under Indonesian conditions. Future research therefore needed to prioritise continuous coal-mine pilot studies under variable seasonal loading, staged Mn and sulfate treatment, long-term residual leaching and stability assessments, media/electrode/membrane life-cycle assessment, and site-specific cost and reliability monitoring before individual technologies could be meaningfully compared for full-scale deployment.

4. Conclusions

No single technology was superior across all AMD and coal mine wastewater conditions. Neutralization was best supported as a treatment stage for acidity correction and Fe/Al removal, whereas adsorption was more defensible as a capacity-limited polishing process. Passive systems could provide long-term treatment where land availability, HRT, hydraulic loading, and seasonal conditions were compatible, while electrocoagulation represented an active option for solids and metal removal whose field applicability depended on reliable power, electrode

management, and sludge handling. Persistent Mn, sulfate, salinity, and residual streams were the principal reasons for progressing from a single process to a treatment train. Biological sulfate reduction, membrane separation, and resource recovery could provide complementary treatment stages, but their applicability depended on operating conditions, infrastructure, residual management, and evidence maturity. The treatment-selection matrix therefore linked measured wastewater chemistry and mass loading with evidence class, study scale, site constraints, and residual-management consequences before a candidate treatment train was selected for pilot verification. Cost and energy remained screening variables rather than ranking criteria because comparable full-scale life-cycle data were limited. For applications in Indonesia, full-scale treatment selection should be based on seasonal monitoring, staged verification, maintenance and operator capacity, residual characterization, site-specific life-cycle cost assessment, and discharge requirements applicable to the relevant permit.

Author Contributions

Fredy Mukti: Conceptualization, Methodology, Investigation, Data Curation, Formal Analysis, Visualization, Writing – Original Draft. Riam Marlina: Conceptualization, Methodology, Validation, Supervision. Fadhillah: Methodology, Validation. Rizto Salia Zakri: Validation. All authors: Writing – Review & Editing.

Funding

This research received no external funding.

Data Availability Statement

No new experimental or field-monitoring data were generated. The review is based on published literature and technical or regulatory sources cited in the manuscript. The Supplementary Materials provide the complete search strategy and search strings, study-selection and retrieval records, study-level extraction for all 64 retained studies, R/S/O/C evidence appraisal, transferability assessment, operational limitations, and full-text disposition.

Competing Interests

The authors declare no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Declaration of Generative AI and AI-Assisted Technologies

During manuscript preparation, the authors used ChatGPT and Claude for language refinement, document structuring, and organization of literature notes. The authors reviewed and revised all AI-assisted material and verified technical statements against the cited sources. The authors remain fully responsible for the accuracy, originality, interpretation, citations, and final content of the manuscript.

Supplementary Materials

Supplementary Materials to this article can be found online at <https://doi.org/10.53623/idwm.v6i2.1322>.

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