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Waste Treatment Plants and Remediation Strategies in Indian Mining Areas: A Technical Review of Effluent Management, Acid Mine Drainage, Tailings Stacking, and Circular-Economy Recovery

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Abstract: India's mining sector, a cornerstone of national industrial growth, generates vast volumes of solid, liquid, and gaseous waste at a time when per-capita water availability has fallen from roughly 5,000 cubic metres in 1950 to about 1,500 cubic metres today. This review synthesises current practice in mine-water treatment, acid mine drainage (AMD) bioremediation, tailings management, sector-specific hazardous waste handling, and the emerging circular-economy recovery of critical minerals from legacy waste. Evidence is drawn from operating case studies including Coal India Limited's community water-utilisation programmes, IIT Guwahati's constructed-wetland research, Hindustan Zinc's Dry Tailing Plant at Zawar, Tata Steel's hexavalent-chromium reduction facility at Sukinda, and the Uranium Corporation of India's radiological effluent controls at Jaduguda. The review finds that the sector is transitioning decisively from passive containment toward active resource recovery, Zero Liquid Discharge (ZLD) systems, and stacked dry tailings, while simultaneously identifying legacy dumps as a viable secondary source of nickel, cobalt, gallium, vanadium, and rare-earth elements.

Keywords: acid mine drainage, dry tailings stacking, hexavalent chromium, constructed wetlands, Zero Liquid Discharge, critical mineral recovery, red mud, jarosite.

1. INTRODUCTION: MINING WASTE AND HYDROLOGICAL STRESS IN INDIA

Mineral extraction in India produces tailings, overburden, process effluent, and acid mine drainage on a scale that has forced a paradigm shift away from simple waste containment toward engineered treatment, resource recovery, and circular-economy thinking. As the country's water stress intensifies, the mining and mineral-processing industry — among the largest consumers of raw water and generators of complex wastewater laden with heavy metals, cyanides, sulfates, and residual reagents — faces mounting regulatory pressure from the Central Pollution Control Board (CPCB) and the Ministry of Environment, Forest and Climate Change (MoEFCC).

In response, mining conglomerates have deployed Effluent Treatment Plants (ETPs), Sewage Treatment Plants (STPs), and advanced dewatering technologies tailored to site-specific geochemistry. The sections that follow examine this infrastructure across five domains: mine-water treatment, AMD bioremediation, tailings stacking, sector-specific hazardous residues, and legacy-waste valorisation.

2. ADVANCED MINE WATER TREATMENT AND EFFLUENT MANAGEMENT

2.1 Chemical and Mechanical Treatment Mechanisms

Dewatering of mine sumps is an operational necessity, but discharge requires rigorous treatment before release. Modern ETPs follow a multi-stage physiochemical sequence: coagulation neutralises the electrostatic charge on colloidal fines, flocculation binds them into settleable flocs, and alkaline dosing raises pH (frequently to ≥8) so that dissolved metal ions precipitate as insoluble hydroxides for mechanical separation in clarifiers and thickeners. Final polishing frequently culminates in Zero Liquid Discharge (ZLD) configurations combining pre-filtration with Reverse Osmosis and

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Ultrafiltration membranes capable of rejecting up to 98% of dissolved solids and recovering as much as 95% of process water. Mobile high-rate clarification units using ballasted flocculation have also been deployed at remote sites, reducing incoming suspended solids from up to 40 ppm to below 4 mg/L even in harsh conditions.

2.2 Socio-Economic Utilisation of Treated Mine Water

The coal sector illustrates how treated discharge is being redirected into regional supply chains rather than simply released. Total mine-water availability across Coal India Limited subsidiaries, NLC India Limited, and Singareni Collieries reaches approximately 9,935.4 Lakh Kilolitres (LKL) annually, of which about 26.3% is directed to community irrigation and drinking supply. The chart below compares annual discharge across the five leading PSU subsidiaries.

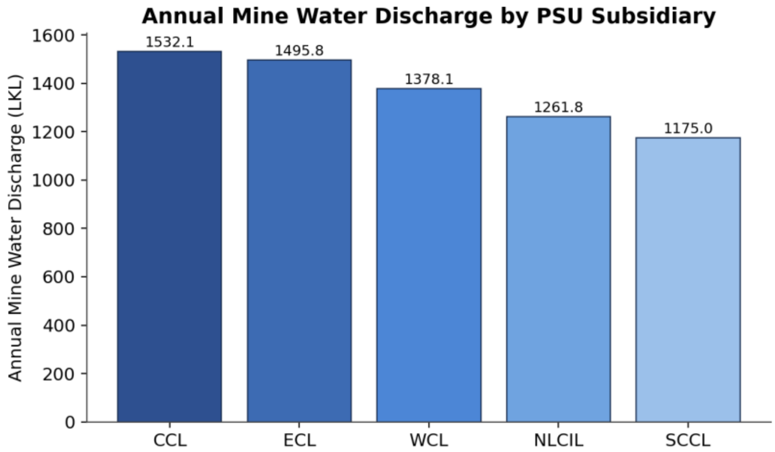

Figure 1. Annual mine water discharge by PSU subsidiary (LKL/year).

Flagship programmes include Western Coalfields Limited's "Coal Neer" bottled-water initiative — RO- and UV-treated mine water distributed by women's Self-Help Groups under BIS and FSSAI certification — and supply MoUs such as WCL's 107.6 lakh cubic metres per year to MAHAGENCO's thermal plants and NLCIL's 19,611 kilolitres/day pipeline to Chennai. At the Bishrampur opencast mine, a flooded 26-acre void has been converted into a pisciculture and eco-tourism site supporting local livelihoods.

3. ACID MINE DRAINAGE: GEOCHEMISTRY AND BIOREMEDIATION

3.1 Formation Mechanics

AMD arises when sulfidic minerals, chiefly iron pyrite, oxidise in the presence of water and air, releasing ferrous iron, sulfate, and hydrogen ions. Acidophilic bacteria such as Thiobacillus ferrooxidans accelerate the conversion of ferrous to ferric iron by up to six orders of magnitude; the subsequent hydrolysis of ferric iron produces the characteristic yellow-orange ferrihydrite precipitate known as "yellow boy" while driving pH down to the 2.0–4.0 range. This acidity mobilises lead, cadmium, copper, zinc, manganese, and nickel, as observed in the Gorbi mine of the Singrauli coalfield.

3.2 Constructed Wetlands and Sulfate-Reducing Bacteria

Because continuous chemical neutralisation is costly and generates large volumes of hazardous sludge, passive Constructed Wetlands (CWs) have become the preferred long-term solution. IIT Guwahati's work on the Northeastern Coalfields demonstrates that anaerobic Sulfate-Reducing Bacteria convert sulfate to hydrogen sulfide, consuming protons and raising pH from below 2.5 to a near-neutral 6.0–8.5 while precipitating metals as stable sulfides. In one horizontal wetland planted with Typha latifolia, total zinc removal reached 95%, though direct plant uptake accounted for only about 1.2% of the removed mass — the bulk (roughly 83%) was retained physically and chemically within the organic substrate. Macrophytes such as Typha orientalis and Phragmites australis are selected for their tolerance of extreme sulfate loads (up to ~9,400 mg/L) and their roles in phytoextraction and phytostabilisation respectively.

3.3 Industrial Symbiosis

At Singrauli, alkaline fly ash from adjacent thermal power plants is used to neutralise AMD acidity, simultaneously

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providing a disposal pathway for a second waste stream. Separately, NIT Rourkela has developed low-cost ceramic adsorbents from coal- and steel-industry waste for organic-dye removal at a fraction of the cost of activated carbon.

4. TAILINGS STORAGE FACILITIES AND THE DRY STACKING REVOLUTION

4.1 Liabilities of Conventional Wet Disposal

Conventional tailings management pipes a 40–50% solids slurry into engineered impoundments retained by embankment dams, often raised by the upstream method. These facilities carry persistent liquefaction and catastrophic-failure risk, and large volumes of process water are lost to evaporation and seepage.

4.2 Dry Tailing Plants (DTP)

Hindustan Zinc Limited commissioned India's first Dry Tailing Plant at the Zawar Mines in Rajasthan (₹96 crore investment, 5 MTPA capacity, FLSmidth technology). The process sequence is: (1) high-rate thickening to ~65% solids; (2) high-pressure filtration (up to 30 bar) yielding an 80–85% solids cake; and (3) mechanical stacking compacted to 95% of maximum dry density, with a 1:3 slope maintained per 10 metres of stack height.

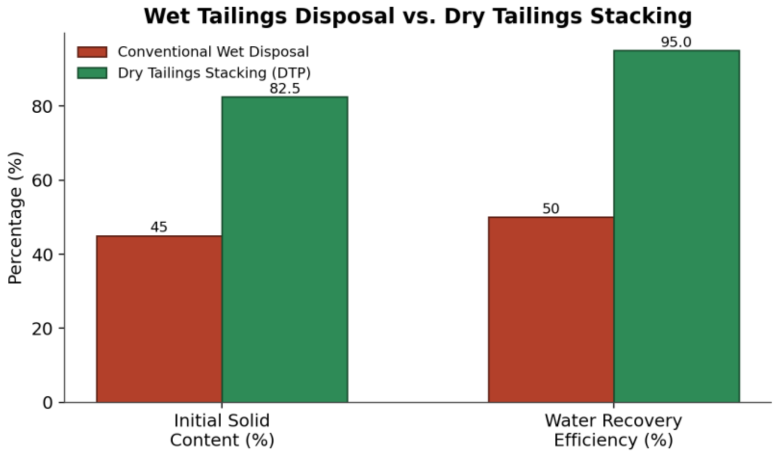

Figure 2. Solids content and water-recovery efficiency: conventional wet disposal versus Dry Tailings Stacking.

The operational payoff has been substantial: specific freshwater consumption at Zawar's mill fell from 0.48 m³/MT in FY 2017-18 to 0.16 m³/MT in FY 2021-22, and the share of tailings recycled as underground paste-fill rose from 0% in FY 2019-20 to 14.05% by FY 2022-23.

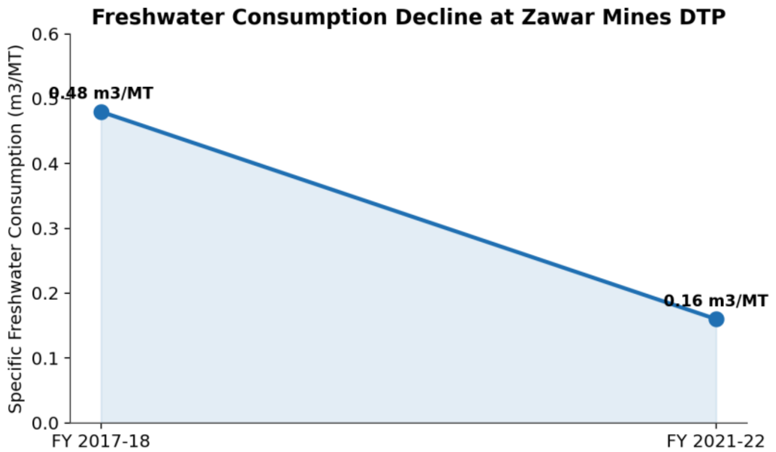

Figure 3. Decline in specific freshwater consumption following DTP commissioning at Zawar Mines.

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5. SECTOR-SPECIFIC EFFLUENT AND HAZARDOUS WASTE TREATMENT

5.1 Chromite Mining: Hexavalent Chromium Remediation

The Sukinda valley in Odisha holds roughly 97–98% of India's proven chromite reserves. Weathering of overburden oxidises inert trivalent chromium into carcinogenic, highly mobile Hexavalent Chromium (Cr(VI)), threatening groundwater and the Brahmani River basin. Tata Steel's ETP, operating at 4,500 kilolitres/hour, doses ferrous sulfate to reduce Cr(VI) to the stable trivalent state, achieving near-100% removal to below 0.005 mg/L before full water recycling. Emerging alternatives include the plant-based reductant Terminalia chebula (developed with CLRI), water-hyacinth phytoremediation removing up to 99.5% of Cr(VI) within a 15-day retention time, and experimental POSEIDON peptide-alginate beads for decentralised purification.

5.2 Uranium Mining: Radiological Effluent Management

At UCIL's Jaduguda, Narwapahar, and Bhatin mines in Jharkhand's Singhbhum Thrust Belt, sulfuric-acid leaching of uraninite ore generates acidic, radioactive barren liquor. This is neutralised with lime to pH 10.5–11.5; coarse sand is separated for underground backfill, while fine slimes are isolated in geomembrane-lined tailings ponds exceeding 30 hectares. Barium chloride is dosed in the ETP to co-precipitate Radium-226 as an insoluble barium-radium sulfate complex, allowing up to 2,400 m^3/day of water to be recycled into the mill circuit.

5.3 Zinc Smelting: From Jarosite to Fumer Technology

Iron impurities in zinc concentrate were historically precipitated as hazardous, leachable jarosite. Stabilising it with 10% Portland cement and 2% lime produces "Jarofix," a pozzolanic matrix stable enough for use as highway subgrade. Hindustan Zinc's Chanderiya smelter is now adopting Zinc Ferrite Fuming ("Fumer") technology, which recovers residual zinc, lead, copper, and silver as fume oxides, eliminates jarosite generation entirely, and produces a clean, iron-and-lime-rich slag usable in cement manufacture while generating 21 MWh of waste-heat-recovered energy.

5.4 Bauxite Mining: Red Mud Dry Stacking

Alumina refining generates roughly 9 million tonnes of highly alkaline red mud annually across NALCO, Hindalco, and Vedanta plants. Dry Mud Stacking dewaters this residue to 72–75% solids for placement in geomembrane-lined ponds with full decant recycling. Classified by CPCB as "High Volume Low Effect Waste" rather than hazardous, red mud is increasingly dispatched to cement plants — Hindalco's Muri refinery alone sent 31,398 MT to ACC Cement in a single fiscal year.

6. ECOLOGICAL RESTORATION OF LEGACY TAILINGS

6.1 Kolar Gold Fields

Roughly 33–40 million tonnes of legacy cyanide-tailings dumps at Kolar Gold Fields, Karnataka, show heavy-metal contamination in the order Manganese > Iron > Arsenic > Nickel > Copper > Zinc > Lead > Cadmium, with arsenic peaking at 28.56 mg/kg near barren land. Remediation combines HCl/EDTA soil washing with phytostabilisation using resilient native species, alongside parliamentary proposals to monetise residual gold in the dumps as an incentive for physical remediation.

6.2 Kudremukh Iron Ore

Following the 2005 Supreme Court-mandated closure of KIOCL, the 100-metre Lakya tailings dam in the high-rainfall Western Ghats required inward bench terracing, staggered gunny-bag crating on steep slopes, and agronomic soil amendment to stabilise the dump and prevent catastrophic siltation of the Bhadra River basin.

7. THE CIRCULAR ECONOMY: TAILINGS AS A SECONDARY ORE BODY

India's National Critical Mineral Mission is systematically resampling legacy sites — Phase I alone covered ten commodities across 367 sites — because processing already-mined material offers 30–60% lower capital expenditure, 2–5 year time-to-production, and 40–80% lower carbon footprint versus greenfield exploration.

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Value Chain / Location	Estimated Stock	Target Critical Minerals	Peak Concentrations	Est. Gross Value (INR)
Chromite Dumps (Odisha)	~442 Mt	Nickel, Cobalt, PGE	Ni 1.3%, Co 1,853 ppm	~0.40 lakh Cr (Ni)
Copper Tailings (HCL)	Variable	Molybdenum, Tellurium, Selenium	Te 106 ppm, Se 152 ppm	~804 Crore
Lead & Zinc (HZL)	~8.5 Mt (Jarosite/Slag)	Antimony, Cadmium	Sb 20% (slime), Cd 4,399 ppm	~496 Crore
Fluorite Dumps (GMDC)	11.2 Mt	REE, Niobium	REE 11,000 ppm, Nb 2,084 ppm	~5,186 Crore
Bauxite Red Mud	~150 Mt	Gallium, Vanadium	Ga 92 ppm, V 970 ppm	~50,832 Crore

Table 1. Estimated critical-mineral reserves in legacy mine waste (national assessment / pilot data).

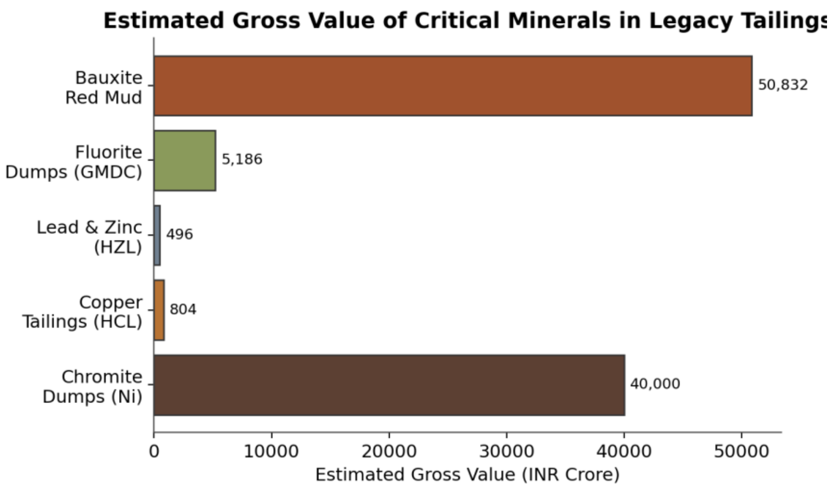

Figure 4. Estimated gross value of critical minerals recoverable from legacy tailings streams.

Concrete pilots are underway across value chains: Hindustan Copper Limited's tailings hold an estimated 1,764 tonnes of molybdenum and 180 tonnes of selenium (₹804.59 crore combined value), targeted for mid-2027 commercial viability. Tata Steel has produced 295 tonnes of Nickel Pig Iron (up to 1.8% nickel) from legacy chromite dumps, while OMC and CSIR-IMMT target commercial nickel and PGE extraction by 2028. Hindustan Zinc has issued global expressions of interest for antimony extraction from silver slimes, and Hindalco has commissioned a 6,000 tonne-per-annum vanadium plant with a gallium recovery facility due by March 2026; NALCO is pursuing a parallel gallium pilot with BARC.

8. CONCLUSION

The management of Indian mining waste has moved decisively from rudimentary disposal toward sophisticated remediation, valorisation, and ZLD protocols. RO-based community programmes such as "Coal Neer" convert mine discharge into a socio-economic asset; constructed wetlands offer a low-energy route to neutralising AMD; and the shift to Dry Tailing Plants removes the systemic liquefaction risk of wet impoundments while cutting freshwater demand. Finally, the strategic recovery of nickel, gallium, antimony, niobium, and PGEs from legacy tailings and red mud illustrates a genuine circular-economy transition — treating historically hazardous waste as a resource rather than a permanent liability, in support of India's clean-energy and critical-mineral self-reliance goals.

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