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Review Article

A Review of Circular Economy Strategies for Mining Waste in India: Challenges, Opportunities, and the Role of Digitalization

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Abstract

India's rapidly expanding economy relies heavily on the mining sector to supply raw materials for energy production, infrastructure development, and industrial growth. However, mining activities generate vast quantities of waste, including overburden, waste rock, and tailings, which pose serious environmental and social challenges. These wastes may release toxic elements and contribute to land degradation, water contamination, and long-term ecological risks. This review examines how circular economy principles can be applied to mining waste management in India to transform waste streams into valuable resources while minimizing environmental impacts. The study evaluates several strategic approaches, including waste minimization at the source, reprocessing of historical tailings to recover residual metals, and upcycling of mineral waste into construction materials such as bricks, blocks, ceramics, and geopolymer binders. The paper also discusses the environmental implications of heavy metal contamination associated with mining waste, highlighting the risks posed by elements such as arsenic, lead, and cadmium in mining regions. In addition, emerging technologies such as digital monitoring systems, advanced mineral processing techniques, and artificial intelligence–based resource management are reviewed as tools that may support more sustainable mining practices. The results indicate that integrating circular economy strategies into India's mining sector could significantly reduce waste volumes, recover valuable metals, and support more sustainable resource utilization. These approaches provide both environmental and economic benefits and represent an important pathway toward responsible mineral resource management.

Keywords: Circular Economy; Mining Waste; Tailings; Waste Valorization; India; Environmental Policy

1. Introduction

India's ambition to become a US$5 trillion economy is intrinsically linked to the performance of its industrial sectors, with mining serving as a foundational pillar (Sahoo et al., 2016). As a global powerhouse, India is the world's second-largest producer of coal and crude steel and the fourth-largest producer of iron ore (Behera et al., 2013). The mining sector's contribution to the nation's Gross Domestic Product (GDP) is approximately 1.8-2.5%, with significant downstream linkages to critical industries like power, cement, and manufacturing (Prasad & Bose, 2001)). This industrial growth, however, is accompanied by a monumental environmental challenge: the generation of enormous volumes of solid waste. It is estimated that the Indian mining industry produces over 170 million tonnes of solid waste annually, primarily comprising overburden, waste rock, and fine-grained tailings from mineral processing (Masto et al., 2011).

Traditionally viewed as a liability, this waste occupies vast tracts of land, poses risks of environmental contamination through acid mine drainage (AMD) and heavy metal leaching, and threatens the stability of ecosystems and local communities (Kinnunen et al., 2022;). The catastrophic failure of tailings dams, though infrequent, can have devastating consequences, as seen in incidents in states like Odisha and Chhattisgarh, leading to environmental destruction and loss of livelihood (Lottermoser, 2010).

In response to these challenges, the concept of a circular economy (CE) offers a transformative framework. Shifting from a linear 'take-make-dispose' model, a circular economy aims to minimize waste and maximize resource value by keeping materials in use for as long as possible (Kinnunen et al., 2022). For the mining industry, this involves reimagining waste as a secondary resource, from which valuable metals and minerals can be recovered, or which can be repurposed into new products (Antony Jose et al., 2024). This approach not only mitigates environmental risks but also enhances resource security, reduces import dependency, and creates new economic opportunities (Sahoo et al., 2013).

This paper investigates the application of circular economy principles to the Indian mining sector. Drawing parallels with global best practices while focusing on the unique Indian context, it addresses the following key questions: 1) What is the current policy and regulatory landscape for mining waste management and circularity in India? 2) What are the viable strategies (reduce, reprocess, upcycle, downcycle) for valorizing mining waste in India, supported by real-world examples? 3) How can digital technologies act as an enabler for waste valorization and a circular transition in the Indian mining industry? By reviewing government policies, industry reports, and academic studies, this paper evaluates the potential to transform India's mining waste from an environmental burden into a cornerstone of a sustainable and self-reliant economy.

2. Methodology and Data

This study is a narrative review based on a comprehensive search and analysis of publicly available literature and data. The information was gathered from a wide range of sources to provide a multi-dimensional perspective on the circular economy in the Indian mining sector (Fig.1). Key sources included government publications from the Ministry of Mines, Ministry of Coal, and the Indian Bureau of Mines (IBM); policy documents and press releases from the Press Information Bureau (PIB); annual reports and sustainability disclosures from major public and private mining companies; and reports from industry bodies such as the Federation of Indian Mineral Industries (FIMI). Academic databases and search engines, including Google Scholar and ScienceDirect, were searched using keywords such as "circular economy in mining," "mine tailings India," "waste valorization," "mining policy India," and "digitalization in mining." The literature was selected based on its relevance to the Indian context, with a focus on data and case studies from 2020 onwards to ensure currency. The gathered information was synthesized and structured according to the established academic format to discuss the policy framework, waste management strategies, and the role of technology in India's transition towards a circular mining economy.

3. The Indian Mining Landscape and Waste Generation

3.1. Overview of India's Mining Sector

India's mining sector is characterized by its vast reserves and diverse mineral portfolio, producing 95 different minerals (Tiwary, 2001). The industry is dominated by the production of fuel minerals, particularly coal, and metallic minerals like iron ore, bauxite, and manganese. In the fiscal year (FY) 2024-25, coal production crossed the one-billion-tonne mark, reaching 1,047.7 million metric tonnes (MMT), while iron ore production hit a record high of 289 MMT (Hudson-Edwards et al., 2011). This robust production is concentrated in a few mineral-rich states, with Odisha, Chhattisgarh, and Jharkhand being the leading producers of coal, iron ore, and bauxite (Sahoo et al., 2016).

The sector is a mix of large public sector undertakings (PSUs) and a growing number of private entities. PSUs like Coal India Limited (CIL) and National Mineral Development Corporation (NMDC) have historically dominated production, but recent policy reforms, particularly the amendment of the MMDR Act, have facilitated greater private sector participation through a transparent auction regime. This has been instrumental in boosting production and attracting investment to meet the surging domestic demand driven by infrastructure development and manufacturing growth under initiatives like 'Make in India' (Singh & Kumar, 2012).

Figure 1: Large-scale open-pit coal mining operation in India illustrating the generation of overburden and waste rock. Such operations play a crucial role in national energy supply but also represent one of the primary sources of mining waste.

3.2. Mining Waste: A Growing Environmental Challenge

The sheer scale of India's mining operations results in the generation of colossal quantities of waste. Mining waste is broadly categorized into overburden/waste rock (material removed to access ore bodies) and tailings (fine-grained residue after mineral processing). In India, tailings generation is estimated to be 10-25% by weight of the total iron ore mined, amounting to millions of tonnes annually (Kakodkar & Sawaiker, 2025; Das et al., 2000). The overburden/waste rock segment constitutes the largest portion of mining waste, accounting for a significant share of the market for waste management (Bian et al., 2010).

This waste poses severe environmental risks if not managed scientifically. Key challenges include:

Land Degradation: Overburden dumps and tailings storage facilities (TSFs) occupy vast areas of land, often leading to deforestation and loss of biodiversity.

Water Pollution: The primary environmental concern is Acid Mine Drainage (AMD), a process where sulfide minerals in waste rock and tailings react with air and water to form sulfuric acid. This acidic leachate can dissolve heavy metals (e.g., arsenic, lead, cadmium), contaminating ground and surface water sources and rendering them toxic to aquatic life and unsafe for human consumption (Tabelin et al., 2018). Studies in mining regions of Goa and Northeast India have documented significant groundwater contamination due to AMD and heavy metal leaching from mine wastes (Yellishetty et al., 2009; Dutta et al., 2020).

Air Pollution: Dust from mining operations, waste dumps, and dry tailings can degrade local air quality. This particulate matter (PM10 and PM2.5) can cause respiratory illnesses in nearby communities and negatively impact vegetation by clogging stomata and reducing photosynthesis (Nayak & Chowdhury, 2018).

Tailings Dam Failures: Although modern engineering standards have improved, the risk of TSF failure remains a critical concern. Breaches can release massive volumes of toxic slurry, causing catastrophic damage downstream. Incidents such as the iron ore 'check-dam' breach in Chhattisgarh and the alumina refinery waste breach in Odisha highlight the devastating potential impact on communities and ecosystems (Lottermoser, 2014).

3.3 Heavy Metal Contamination Associated with Mining Waste in India

Mining activities are widely recognized as one of the major anthropogenic sources of heavy metal contamination in the environment (Maleknia et al., 2025). During the extraction and processing of mineral resources, large volumes of waste materials such as overburden, waste rock, and tailings are generated. These materials often contain residual concentrations of toxic metals that may be mobilized through weathering processes, acid mine drainage, or leaching from tailings storage facilities (Mazhari et al., 2013).

In India, several mining regions have reported environmental concerns related to the release of heavy metals from mining waste. Among the most commonly reported toxic elements are arsenic, lead, and cadmium, which can dissolve in acidic drainage generated from sulfide-bearing waste materials. When released into surrounding environments, these metals may contaminate surface water, groundwater, and soils, posing risks to ecosystems and human health.

Iron ore and coal mining regions in states such as Goa, Jharkhand, Odisha, and parts of Northeast India have experienced localized contamination associated with tailings and waste rock deposits. Acid mine drainage generated from exposed sulfide minerals can significantly increase the mobility of heavy metals, allowing them to migrate into nearby rivers, agricultural lands, and drinking water sources. Long-term exposure to these contaminants has been associated with ecological degradation and potential health hazards for local communities.

Effective management of heavy metal contamination therefore represents a critical component of sustainable mining practices. Approaches such as improved tailings management, encapsulation of reactive waste materials, monitoring of groundwater quality, and the recovery of metals from tailings can reduce environmental risks while also supporting circular economy strategies. By integrating environmental monitoring with resource recovery technologies, the mining sector can simultaneously mitigate pollution and recover valuable metals from previously discarded waste streams.

4. Institutional and Policy Framework for Mining Waste in India

India's approach to mining and environmental management is governed by a multi-layered legal and institutional framework. While historically focused on regulation and revenue, recent policy shifts reflect a growing emphasis on sustainability, resource efficiency, and the principles of a circular economy.

4.1. Key Regulations Governing Mining and Environment

The regulatory landscape for mining is primarily shaped by the central government, with implementation and enforcement responsibilities shared with state authorities. Key legislations include:

The Mines and Minerals (Development and Regulation) Act, 1957 (MMDR Act): This is the principal legislation governing the mining sector. Significant amendments in 2015, 2021, and 2023 have modernized the Act, introducing a transparent auction-based system for granting mineral concessions and provisions to boost exploration and production of critical minerals (Kumar & Maiti, 2015).

The Mines Act, 1952: This act focuses on the health, safety, and welfare of workers in mines. It is administered by the Directorate General of Mines Safety (DGMS) under the Ministry of Labour and Employment (Lottermoser, 2014).

Mineral Conservation and Development Rules (MCDR), 2017: Framed under the MMDR Act, these rules mandate sustainable and scientific mining practices. They include crucial provisions for the preparation of Progressive and Final Mine Closure Plans, which require detailed strategies for land reclamation, rehabilitation, and the management of waste dumps and tailings (Lottermoser, 2010). The rules explicitly require that overburden, waste rock, and tailings be stored in separate, secured dumps to prevent environmental degradation.

Environment (Protection) Act, 1986: This is the umbrella legislation for environmental protection. Under this Act, several rules have been notified that are relevant to mining, including the Solid Waste Management Rules (2016), Hazardous and Other Wastes Management Rules (2016), and the Environmental Impact Assessment (EIA) Notification (2006), which mandates environmental clearance for all new mining projects (India Briefing, 2024).

Institutional oversight is provided by the Ministry of Mines, the Indian Bureau of Mines (IBM), the Ministry of Environment, Forest and Climate Change (MoEFCC), and the Central and State Pollution Control Boards (CPCB and SPCBs), which set and enforce environmental standards for air and water quality (Trade.gov, 2024).

4.2. Policy Impetus for a Circular Economy in Mining

Recognizing the limitations of a linear economic model, the Indian government has initiated several policies that directly or indirectly promote a circular economy in the mining sector.

"The National Mineral Policy (NMP) 2019 provides a vision of how India should implement future policy to accelerate the growth of the mining sector... It assures a regulatory environment that is conducive for 'ease of doing business with simpler, transparent and time-bound procedures'." (Sahoo et al., 2016)

The NMP 2019 explicitly encourages the recycling of materials and the adoption of zero-waste mining practices (Lottermoser, 2011). This vision is being operationalized through targeted missions and schemes:

National Critical Mineral Mission (NCMM): Launched in 2025, the NCMM aims to secure a resilient supply chain for minerals vital to green technologies and strategic sectors. A key objective of the mission is to strengthen value chains by enhancing recycling and recovering minerals from secondary sources like mine tailings and industrial waste (Sahoo et al., 2013; 2016).

Incentive Schemes for Recycling: To support the NCMM, the government has introduced incentive schemes for the recycling of critical minerals. For instance, the Union Budget 2025-26 eliminated customs duties on the scrap of several critical minerals to encourage domestic processing and recycling (Hudson-Edwards et al., 2011).

Single Window Clearance System (SWCS): To streamline the complex approval process for mining projects, the Ministry of Coal launched the SWCS portal. This digital platform aims to provide a single point of access for obtaining all necessary clearances, including environmental and forest approvals, thereby reducing delays and improving transparency (Sahoo et al., 2016). These policy initiatives signal a clear intent to move towards a more sustainable and resource-efficient mining industry, where waste is increasingly viewed as a potential resource rather than a disposal problem.

5. Circular Economy Strategies for Mining Waste in India

A holistic approach to mining waste management involves a hierarchy of strategies, from preventing waste generation at the source to safely disposing of the final residues. This section examines these strategies—Reduce, Reprocess, Upcycle, and Downcycle—within the Indian context, drawing on emerging practices and research.

5.1. Reduce: Waste Minimization at the Source

Minimizing waste generation at the source remains the most effective circular-economy strategy in the mining sector. In practice, this approach focuses on improving process efficiency, reducing dilution, and maximizing recovery of valuable minerals before waste is generated. Advanced technologies such as sensor-based ore sorting, selective mining, and digital process control systems have emerged as promising solutions for reducing the volume of tailings at the earliest stages of mineral processing.

In India, source-reduction initiatives are gradually gaining attention as mining companies seek to optimize resource utilization and reduce waste-management costs. Although large-scale deployment of sensor-based ore sorting is still limited, several operations have initiated pilot-scale trials aimed at rejecting waste rock before grinding and flotation. These technologies are particularly relevant for Indian iron ore and base-metal mines, where heterogeneous ore bodies make selective mining and early waste rejection critical for productivity and environmental performance.

Pilot studies conducted in selected Indian iron ore mines have demonstrated that pre-concentration using optical and XRT-based sorting can significantly reduce processing volumes, leading to measurable reductions in tailings generation, energy consumption, water usage, and chemical reagent requirements (Kinnunen et al., 2022). While industrial-scale adoption is still evolving, these early implementations indicate substantial potential for integrating source-reduction technologies within India's broader circular-economy framework for mining (Ratha et al., 2016).

5.2. Reprocess: Recovery of Metals and Minerals

Reprocessing of historical and current tailings represents a major opportunity for recovering residual metals and reintroducing valuable materials back into the production cycle. Many older tailings deposits in India still contain significant quantities of zinc, lead, iron, gold, silver, and critical minerals, making them suitable targets for re-mining under modern technological and economic conditions.

A prominent industrial example is Hindustan Zinc Limited's (HZL) tailings reprocessing initiative at the

Rampura Agucha Mine, one of the largest zinc–lead mines in the world. HZL has announced plans to develop India's first large-scale tailings reprocessing plant, with a proposed capacity of approximately 10 million tonnes per annum (Mtpa). The project aims to recover zinc, lead, and silver from legacy and current tailings, leveraging advanced mineral processing techniques to extract residual metals that were unrecoverable using older technologies.

This initiative demonstrates the feasibility and commercial relevance of re-mining waste streams in India. It also aligns with the government's increasing focus on "urban mining" of tailings and secondary deposits to meet future demand for critical and strategic minerals (Singh & Kumar, 2012). Through such industrial-scale examples, reprocessing is emerging as a vital component of India's circular-economy strategy—simultaneously reducing environmental liabilities and unlocking new economic value from previously discarded materials.

5.3. Upcycle: Creating High-Value Products

Upcycling involves transforming mineral waste into higher-value products that can replace conventional raw materials in construction, ceramics, geopolymers, and other industrial applications. This approach is gaining considerable traction in India due to the dual pressures of mineral-waste accumulation and rising demand for sustainable construction materials.

Eco-Friendly Bricks and Blocks: One notable example comes from the iron-ore mining belt of Goa, where researchers have successfully produced eco-friendly composite blocks using 100% iron ore tailings (IOTs) as a replacement for natural sand (Kakodkar & Sawaiker, 2025). These blocks have demonstrated compressive strengths meeting or exceeding the requirements of Indian building standards, indicating strong potential for commercial adoption. The use of IOT-based blocks not only reduces the extraction of natural sand but also provides a productive outlet for the large volumes of tailings generated by local mining operations.

Ceramic Tiles and Construction Materials: Several studies in India have shown that IOTs can replace up to 40% of conventional raw materials in ceramic tile production without compromising product performance (Das et al., 2000). Such applications offer a valuable pathway for utilizing fine tailings fractions that are otherwise difficult to manage (Ebadi and Zahmir, 2026).

Geopolymers and Cementitious Products: Tailings from iron ore, bauxite, and copper mines have also been explored as precursors for geopolymer binders, presenting a lower-carbon alternative to Portland cement. These materials exhibit strong mechanical performance and lower environmental footprints, making them an attractive option for green construction technologies (Kinnunen et al., 2022).

Overall, upcycling of mineral tailings into building materials represents a scalable, economically viable, and environmentally beneficial approach that aligns closely with India's circular-economy goals for the mining sector.

5.4. Downcycle: Large-Volume, Low-Value Applications

Downcycling involves using the bulk of mining waste in its original form for large-volume applications, typically with lower economic value. This is a crucial strategy for managing the vast quantities of overburden and waste rock.

Mine Backfilling: A common practice is to mix tailings with cement to create a paste, which is then used to backfill underground voids. This technique, known as paste backfill, improves mine stability, reduces surface waste disposal, and allows for the recovery of pillars containing valuable ore (Behera et al., 2021). HZL is one of the companies in India actively using this technology (HZL, n.d.).

Construction and Infrastructure: Overburden and waste rock are widely used as fill material for road construction, railway embankments, and land reclamation projects. Coal PSUs in India are actively promoting the use of overburden to reduce reliance on river sand for construction, thereby protecting riverine ecosystems (Tripathy et al., 2015).

5.5. Dispose: Safe Storage and Mine Closure

Even with the best CE strategies, some residual waste will always remain. The final step in the hierarchy is the safe and permanent disposal of this waste. This involves engineered Tailings Storage Facilities (TSFs) designed to ensure long-term geotechnical stability and prevent environmental contamination. Indian regulations, such as the MCDR 2017, mandate detailed Mine Closure Plans that include measures for reclaiming and rehabilitating waste dumps and TSFs (Lottermoser, 2010). The transition towards "dry stacking" of tailings, which involves dewatering the slurry to create a dense, stable stack, is a global best practice that reduces water consumption and minimizes the risk of dam failure

(Kinnunen & Kaksonen, 2019). Companies like HZL are progressively moving towards dry stacking to enhance the safety and sustainability of their operations (HZL, n.d.).

6. Digital Technologies Supporting Waste Valorisation in India

The transition to a circular economy in the resource-intensive mining sector is heavily dependent on data, transparency, and process optimization. Digital technologies are emerging as powerful enablers, helping to bridge the gap between waste generation and its valorization (Berg et al., 2020, as cited in Kinnunen et al., 2022). In India, the push for 'Digital India' is converging with the mining sector's need for modernization, creating a fertile ground for technological adoption.

6.1. Data, Monitoring, and Environmental Compliance

Effective waste management begins with accurate data. Digital tools are revolutionizing how mining companies monitor their environmental footprint and manage waste streams.

IoT and Sensor Networks: The deployment of Internet of Things (IoT) sensors in and around mining sites allows for real-time monitoring of critical environmental parameters. Sensors can track air quality (PM2.5, PM10, SOx), water quality in tailings ponds and nearby water bodies (pH, heavy metal content), and geotechnical stability of waste dumps and TSFs (Kinnunen & Kaksonen, 2019). This continuous data stream enables proactive management, allowing operators to detect potential issues like leachate seepage or dust exceedances before they become major environmental incidents.

Satellite and Drone Imagery: Remote sensing technologies provide a macro-level view of mining operations. Satellite imagery can be used to monitor land-use changes, track the expansion of waste dumps, and assess the progress of land reclamation and afforestation efforts (Edraki et al., 2014). Drones offer high-resolution mapping of waste volumes and can be equipped with sensors for more detailed environmental monitoring.

These technologies are also crucial for regulatory compliance. The PARIVESH portal, India's single-window system for environmental clearances, is increasingly integrating digital data submission, making the compliance reporting process more transparent and data-driven (Maiti & Jaiswal, 2008).

6.2. Process Optimization and Waste-to-Resource Matching

Digitalization enhances the efficiency of CE strategies by optimizing processes and creating new market linkages for waste materials.

AI and Digital Twins: Artificial Intelligence (AI) and machine learning algorithms can analyze vast datasets from sensors and operations to optimize mineral processing, thereby reducing waste generation at the source. A "digital twin"—a virtual model of a physical mine—allows operators to simulate different scenarios to maximize resource recovery and minimize environmental impact before implementation (Tiwary, 2001).

Digital Platforms for Industrial Symbiosis: A key challenge in creating a circular economy is connecting waste generators with potential users. Digital platforms can act as marketplaces for secondary raw materials. The recently launched National Non-Ferrous Metal Recycling Website in India is a step in this direction, aiming to create a comprehensive database of recyclers, dismantlers, and other stakeholders to improve coordination and transparency in the value chain (Tabelin et al., 2018). Such platforms can facilitate industrial symbiosis, where the waste from one industry becomes the feedstock for another.

By providing accurate, real-time data on the availability, quality, and location of mining waste, digital technologies can help overcome informational barriers and unlock the economic potential of these secondary resources, paving the way for a more circular and sustainable mining sector in India.

7. Discussion

The transition towards a circular economy in the Indian mining sector presents a complex interplay of immense opportunities and significant challenges. While the conceptual framework and policy intent are increasingly aligned with global sustainability goals, the on-ground implementation is still in its early stages. The review highlights that India is not merely adopting generic CE principles but is tailoring them to its specific economic and environmental context, particularly through the strategic lens of resource security and the 'Atmanirbhar Bharat' (self-reliant India) initiative.

The primary opportunity lies in the sheer volume and latent value of mining waste. As demonstrated by the potential recovery of critical minerals and the successful upcycling of tailings into construction materials, India's mining waste dumps can be reconceptualized as national resource reserves (Kakodkar & Sawaiker, 2025). This "waste-to-wealth" approach aligns perfectly with national priorities of reducing import dependence, creating jobs, and fostering domestic manufacturing. The government's proactive stance, evidenced by the MMDR amendments and the NCMM, provides a crucial top-down push, creating an enabling environment for investment in waste valorization technologies (Sahoo et al., 2013).

However, several barriers impede this transition. Firstly, there is a significant technological and infrastructural deficit. While advanced reprocessing and digital monitoring technologies exist globally, their adoption in India is limited, especially among smaller mining operations. The high capital expenditure required for setting up reprocessing plants and digital infrastructure is a major deterrent (Ratha et al., 2016). Secondly, regulatory frameworks, despite recent reforms, can be complex and fragmented. The process of obtaining clearances for waste processing facilities can be time-consuming, and there is a lack of clear, standardized guidelines for the use of waste-derived materials in various applications, which creates market uncertainty. Thirdly, the logistical challenge of transporting vast quantities of low-value waste from remote mine sites to processing centers or markets can render many CE initiatives economically unviable. Finally, social acceptance and building trust with local communities, who are often the most affected by the negative impacts of mining, is paramount for the long-term success of any waste management project.

Compared to the more mature institutional frameworks in regions like the EU, as described by Kinnunen et al. (2022), India's CE policy for mining is still evolving. While the EU's approach is driven by stringent landfill regulations and established markets for secondary materials, India's approach is more strongly linked to strategic resource security and economic development goals. The success of this transition will depend on bridging the implementation gap through a concerted effort involving policy-makers, industry, academia, and financial institutions to de-risk investments, standardize processes, and build robust value chains for secondary raw materials.

8. Conclusion

The Indian mining sector stands at a critical juncture where the adoption of circular economy principles is no longer a choice but a necessity for sustainable growth. This review has established that India possesses both the resource potential in its vast quantities of mining waste and the emerging policy framework to transition from a linear to a circular model. The strategies of reducing waste at the source, reprocessing tailings for valuable minerals, upcycling mineral fractions into high-value products like construction materials, and downcycling bulk waste for infrastructure are all technically feasible and are being demonstrated in pockets of excellence across the country.

The economic case for valorizing mining waste is compelling, offering pathways to enhance resource security, particularly for critical minerals, reduce environmental liabilities, and generate new revenue streams. The government's policy reforms and missions provide a strong directional push, but their success hinges on effective implementation. Key challenges related to technology access, financial viability, regulatory clarity, and logistical constraints must be systematically addressed.
Digitalization emerges as a critical enabler, offering the tools for transparent monitoring, efficient process control, and the creation of market linkages necessary for a thriving circular ecosystem. Ultimately, transforming India's mining waste into a national asset requires a holistic and collaborative approach. By integrating innovative technologies, fostering strategic partnerships between industry and research institutions, and ensuring a stable and supportive regulatory environment, India can pave the way for a mining sector that is not only economically productive but also environmentally responsible and resilient for the future.

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Declarations

Data and code availability

All data generated or analyzed during this study are available from the corresponding author upon reasonable request. No computational code was used in this study.

Conflicts of interest

The authors announced that they have no known conflicts of interest or personal relationships that could have appeared to influence the work reported in this manuscript.

Ethical approval

The authors declare no ethical issues; the research was carried out in full agreement with ethical standards. Also, this paper is neither under Review nor published elsewhere.

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