

NATIONAL SEMINAR ON

Indian Mining

Present Scenario &
Future Perspective



25th & 26th July
2025



Organised by :

**MINING ENGINEERS
ASSOCIATION OF INDIA**

NAGPUR CHAPTER

FLS

EmpEow

erindr

eer throughp and enironmental
peormance at lower operating costs.

This latest generation high-pressure grinding roll is the right choice for energy-efficient comminution technology to meet the challenges of complex ores as well as rising energy prices.

Whether it's a new machine or an upgrade for an existing unit, the HPGR Pro takes your grinding operations to the next level. You benefit from more throughput, better efficiency and reliability. With no water or grinding media required, the HPGR Pro also offers you a significant reduction in energy consumption and energy costs.

Your beunfitsfi

- Up to 20% more throughput
- Up to 15% lower energy consumption
- Up to 30% longer-lasting rolls
- Improved process and maintenance through advanced digital tools
- No grinding media required

➤ www.fls.com



PIONEERING RESPONSIBLE MINING & INCLUSIVE GROWTH

A NEW ERA AT SURJAGARH

India's Largest Electrified Mining Fleet

- 6 electric excavators, 5 electric drill machines
- 9 battery-operated loaders, 56 battery-operated haul trucks
- 12 electric light vehicles

Impact

- **Reduced** carbon footprint
- **Zero-waste** mining initiatives



Towards 100% Green Power

- Planned **86 MW** renewable energy for mine and plant operations

EMPOWERING WOMEN, TRANSFORMING COMMUNITIES

Skilling & Livelihoods

- **70+** women trained in construction trades
- **150+** women employed in garment unit

Fostering Entrepreneurship & Self-reliance

- **60+** women in livelihood programs
- **210+** households practicing backyard farming

Sports & Global Education

- **50+** medals won by girls at Lloyds Sports Academy
- **2 girls** pursuing degrees in Australia



Driving Change & Security

- **30+** women securing sites
- **Women** operating heavy vehicles and machinery

Women in Mining & Technical Roles

- **250+** women trained
- **270+** employed in core operations

WASTE TO WEALTH

India's First BHQ Beneficiation Plant

- Upgrading **low-grade ore to 67% Fe**
- Resource augmentation from **89 MT to 857 MT**
- Creating **1,000** local jobs
- Supports **forest conservation** and reduces emissions



EMPOWERED COMMUNITIES, GREENER GROWTH, STRONGER INDIA AHEAD.



Building a concrete foundation for a sustainable future

UltraTech Cement Limited is the flagship cement company of the Aditya Birla Group. A USD 8.9 billion building solutions powerhouse, UltraTech is the largest manufacturer of grey cement, ready-mix concrete (RMC) and white cement in India. With a consolidated grey cement capacity of 192.26 MTPA, it is the third largest cement producer in the world, excluding China. UltraTech is the only company globally (outside of China) to have 175+ MTPA of cement manufacturing capacity in a single country. The Company's business operations span UAE, Bahrain, Sri Lanka and India.

With a diverse portfolio of products & solutions ranging across grey cement, white cement, RMC and building products, UltraTech is a 360° building solutions provider. UltraTech has a network of over 1.4 lakh channel partners across India. UltraTech has 34 integrated units, 34 grinding units, 9 bulk packaging terminals, and 5 jetties. In the white cement segment, UltraTech goes to market under the brand name of Birla White. It has two white cement units and three putty units, with a current capacity

of 2.6 MTPA. UltraTech has 395 RMC units in 155 cities across India. UltraTech is committed to driving sustainability across the value chain of its operations. The focus areas are decarbonisation, circular economy, biodiversity management, water positivity, safe operations and community development. UltraTech is a founding member of Global Cement and Concrete Association (GCCA) and is a signatory to the GCCA 'Climate Ambition to deliver Net Zero Concrete by 2050'. UltraTech has adopted new age tools like the Science Based Targets Initiative (SBTi), Internal Carbon Price and Energy Productivity (#EP100) as part of its efforts to accelerate adoption of low carbon technologies and processes across its value chain and thus reduce carbon footprint over the life cycle.

As part of its CSR, UltraTech reaches out to more than 1.8 million beneficiaries in over 500 villages in 16 states across India, covering areas of education, healthcare, sustainable livelihoods, community infrastructure and social causes.

UltraTech Cement Limited

Registered Office: 2nd floor, 'B' Wing, Ahura Centre, Mahakali Caves Road, Andheri (East), Mumbai – 400093
Tel: 022 6691 7800 Fax: 022 6692 8109 website: www.UltraTechcement.com



AN ADITYA BIRLA GROUP COMPANY



PROCEEDINGS

NATIONAL SEMINAR ON

Indian Mining

Present Scenario &
Future Perspective

25th & 26th July, 2025



Organised by :

**MINING ENGINEERS
ASSOCIATION OF INDIA**

NAGPUR CHAPTER



ORGANISING COMMITTEE

CHIEF PATRONS

Shri Peeyush Narayan Sharma,
Controller General, Indian Bureau of Mines &
Chairman, Mining Engineers' Association of India, Nagpur Chapter.

PATRONS

Shri Pankaj Kulshrestha,
Chief Controller of Mines, MES, IBM, Nagpur.

Shri S. N. Mathur,
President, Mining Engineers' Association of India, Headquarters, Hyderabad.

Shri D. B. Sundara Raman,
Vice President, Mining Engineers' Association of India, Headquarters, Hyderabad.

CONVENERS

Dr. Yogesh G. Kale,
Controller of Mines (CZ), IBM, Nagpur & Hon. Secretary, MEAI, Nagpur Chapter.

Shri V.J.K. Babu,
Controller of Mines (MDR), IBM, Nagpur.

Shri Manish Maindiratta,
Controller of Mines (TMP), IBM, Nagpur

Shri Parag Tadlimbekar,
Superintending Mining Geologist, IBM, Nagpur.

ORGANISING SECRETARIES

Shri Gumna Ram,
Deputy Controller of Mines I/C, Nagpur Regional Office, IBM, Nagpur.

Shri Ashish Mishra,
Deputy Controller of Mines, MDR Division, IBM, Nagpur.

Shri Gaurav Sharma,
Mineral Economist, IBM, Nagpur

JOINT ORGANISING SECRETARY

Shri Arun S. Chachane,
Assistant Controller of Mines, IBM, Nagpur & Joint Secretary, MEAI, Nagpur Chapter.

TREASURER

Shri A. D. Selokar,
Mineral Economist, IBM, Nagpur & Treasurer, MEAI, Nagpur Chapter.

MEMBERS

Shri G. Ram, Organising Secretary

Shri Ashish Mishra, Organising Secretary

Shri Gaurav Sharma, Organising Secretary

Shri Arun Chachane, Joint Organising Secretary



Foreword.....

It is with immense pride and pleasure, I welcome all esteemed delegates, academicians, industry professionals, researchers, and policymakers for the National Seminar on **“Indian Mining-Present Scenario & Future Perspective”**, organized by the Mining Engineers Association of India (MEAI), Nagpur Chapter.

This seminar marks a significant milestone, convening policy makers and practitioners to engage in constructive dialogue on the evolving dimensions of India’s mining landscape. The breadth of research contributions received reflects our community’s commitment to technological advancement, legal insight, and sustainable innovation in mineral development.

Structured around six critical themes, the seminar provides a panoramic view of the sector:

Mining Present and Future explores the evolving trajectory of India’s non-coal mining sector, including current trends and future outlook. Discussions include ore types, reserves, exploration methods, graphite processing within a global context, and India’s readiness to lead in resource beneficiation and supply chain geopolitics.

Legislative Aspects of the Mineral Industry examines major legal reforms, landmark Supreme Court judgments such as Mineral Area Development Authority vs. Steel Authority of India, and notifications redefining mineralized lands-shedding light on the dynamic interplay between governance and industrial progress.

Underground Mining offers a technical deep dive into stoping methods suitable for thick and wide ore bodies, compares overhand and underhand sequences with cemented paste fill, and features case studies on crown pillar stability during the transition from open-pit to underground operations.

New Age Technologies for the Mineral Industry showcases transformative innovations including Artificial Intelligence (AI), Machine Learning (ML), Internet of Things (IoT), and space mining. Topics range from AI applications in sand and aggregate industries to converting mining waste into nano-materials and exploring the promise of deep seabed mining.

Sustainable Mining Techniques highlights best practices in safe and eco-conscious operations, with attention to controlled blast vibrations, sustainable explosive use, and mine reclamation-emphasizing environmental stewardship.

Critical Minerals brings into focus strategic resources essential for national defense, renewable energy, and technological advancement. Deliberations include pathways for critical mineral exploration, secondary extraction techniques for lithium, and India’s positioning in the 2025 global landscape.

Over these two days, this seminar will foster meaningful discourse, interdisciplinary collaboration, and forward-looking strategies essential to shaping the future of Indian mining. I commend my team of MEAI Nagpur Chapter for curating this exceptional platform and believe the outcomes will significantly benefit for policy, research, and practical advancements.

As Chief Patron and Chairman of MEAI, Nagpur Chapter, I extend my best wishes to all participants and encourage active engagement in the insightful discussions ahead-toward a resilient, responsible, and innovative mining future.

Peeyush Narayan Sharma

Chief Patron and Chairman, MEAI, Nagpur Chapter



CONTENTS

Theme/Title	Page No.
-------------	----------

Mining Present and Future

- | | |
|---|----|
| 1. Indian Non-Coal Mining-Present Scenario and Future Perspective –
Gaurav Sharma and Atul Brice, Indian Bureau of Mines | 3 |
| 2. Present Scenario and Future Perspective of Mining in Jammu and Kashmir, India
Dr. Raj Kumar, Deputy Director, Geology & Mining Department, J &K | 9 |
| 3. Review of Ore types, Reserves & Resources, Exploration, Production & Processing of Indian Graphite with reference to Global Scenario-
Anirban Das, Anirban Das, Rupendra Singh Rathore, Dr Rajiullah Khan, Nipam Joshi and Arjun Deshpande, Indian Bureau of Mines | 15 |
| 4. Graphite: An overview on global demand, supply chain & geopolitics with Indian perspective-
Rupendra Singh Rathore, Anirban Das, Nipam Joshi and Anirban Paul, Indian Bureau of Mines | 22 |

Legislative Aspects of Mineral Industry

- | | |
|--|----|
| 1. Major Legal Reforms in India's Mining and Mineral Sector-
Rajiv Kumar, Pavankumar Kantreddy and Sneha Chodankar, Fomento Resources Pvt. Ltd. | 29 |
| 2. Analysis and impact of the Nine Judge Bench Judgement of the Hon'ble Supreme Court of India in the case of Mineral Area Development Authority (MADA) & ANR. Vs M/S Steel Authority of India (SAIL) & ANR. Etc. In Civil Appeal Nos 4056-4064 of 1999, dated July 25th 2024 and August 14th 2024 on the Mining Industry and Way Forward-
Vijay Singh A. R., Chartered Accountant | 36 |
| 3. Call it mineral land-
Dr Meda Venkataiah, Director, M/s. MSPL Limited, RMML & AISL, Hosapete | 50 |
| 4. Drone Adoption in Indian Mining: Regulatory Trends and Global Opportunities-
Sanjeevani Jawadand, Shri Mathuradas Mohota College of Science, Nagpur | 52 |

Underground Mining

- | | |
|--|----|
| 1. Stoping Methods for Thick and Wide Orebody-
Dr. M. N. Bagde, A. G. Sangode & A. K. Raina, CSIR-CIMFR, Nagpur | 59 |
| 2. Comparative analysis of Overhand vs Underhand stoping sequence with cemented paste fill.-
Rohan Jolly Abraham, Shubham Bhargava, John Loui Porathur, Nageswara Rao Kolikipogu, Rohit Meshram and Vinod Kumar Jagapthal, CSIR-CIMFR, Nagpur | 65 |
| 3. Evaluation of stability of crown pillar during transition from open pit to underground mining- A case study-
Aakanksha Sunil Borkar, Saloni Abhay Bhise, Nageswara Rao Kolikipogu, John Loui Porathur and Vinod Kumar Jagapthal, CSIR-CIMFR, Nagpur | 69 |

New Age Technologies for Mineral Industry

- | | |
|---|----|
| 1. World's Largest HPGR 30/20 Pioneering Sustainable Iron Ore Plant Design in India-
A. Janardhanan and T. Mackert, FLSmidth Mining Technologies GmbH | 77 |
|---|----|

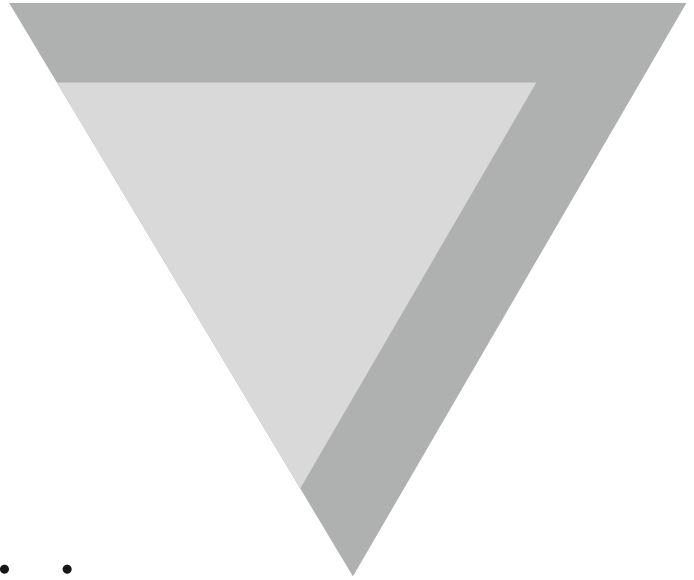
2. Applications of Artificial Intelligence (AI), Machine Learning (ML), and the Internet of Things (IoT) in the Mining Industry for Overall Improvement towards Sustainable & Green Mining-	81
Dhananjay Kumar, Sr GM & Head Mines GHCL Limited	
3. Need of R&D and AI application for Aggregate & Sand Industry in India -	87
Dr. Ramesh Murlidhar Bhatawdekar et al., Department of Mining Engineering, Indian Institute of Technology, Kharagpur	
4. Can Space Mining Support a Sustainable Future ?-	92
Daksha Vyas, Daksha Vyas, Pratik Godbole and Kirtikumar Randive, Department of Geology, RTM Nagpur University	
5. Transforming Mining Waste into Sustainable Nano- materials: Techniques, Applications, and Economic Potential-	93
Kaustub, PG Deshpande, Pratik Godbole and Kirtikumar Randive, PG Department of Geology, RTM Nagpur University	
6. Opportunities and Challenges in of Deep Seabed Mining: An Overview-	98
Rutuja Dhengre, Rutuja Dhengre, Pratik Godbole and Kirtikumar Randive, PG Department of Geology, RTM Nagpur University	

Sustainable Mining Techniques

1. Sustainable Mining Development with Best Management Practices-	105
Dr. Gurdeep Singh, Advisor, NORMI Research Foundation; Founder Member, Centre of Mining Environment, ISM Dhanbad	
2. Analysis of Controlled Blast Ground Vibration Insight of Structure Natural Frequency-	107
G C Naveen & Gopinath G Scientists, NIRM Bengaluru	
3. Safe & Sustainable Use of Explosives-	111
Dr. G.K. Pradhan, Professor & Dean AKS University (Satna)	
4. Reclamation Techniques in Mines: A Case Study Approach to Sustainable Land Recovery in India-	115
Abhishek Bhadang, Priyesh kumar and K M Mulay, RCERT, Chandrapur	

Critical Minerals

1. Unlocking the pathways through knowledge sharing for Critical Mineral investigation as exploration Geologist in nation building mission-	119
Satish Shenwai, Consultant	
2. Sustainable Lithium Supply through Secondary Extraction Technologies-	121
Ms. Krutika Jangale, Krutika Jangale, Pratik Godbole and Kirtikumar Randive, PG Department of Geology, RTM Nagpur University	
3. Critical Minerals for India's Defence Regime-	124
Shantanu Prajapati, Pratik Godbole, and Kirtikumar Randive, PG Department of Geology, RTM Nagpur University	
4. Critical Minerals Scenario of India in 2025: Geopolitical Risks, Domestic Challenges, and the Path to Self-Reliance-	125
Tejal Nirwan, Tejal Nirwan, Pratik Godbole, Sanjeevani Jawadand and Kirtikumar Randive I PG Department of Geology, RTM Nagpur University	



Mining Present and Future





Indian Mining Industry – Present Scenario and Future Perspective...

Gaurav Sharma*, Atul Brice **

* Mineral Economist ** Junior Mining Geologist

Indian Bureau of Mines, Nagpur

ABSTRACT

India is endowed with a vast array of mineral resources, making mining a critical component of the country's economy and industrial development. India's mining sector plays a pivotal role in the nation's economic development by supplying critical mineral raw materials to core industries such as power, steel, cement, and infrastructure. The mining industry in India contributes approximately 2.5% to the national GDP and is a major source of employment. With its rich geological diversity, India produces around 95 different types of minerals, including fuel minerals like coal and lignite, metallic minerals like iron ore and bauxite, and non-metallic minerals like limestone and mica. As the country aspires to become a \$5 trillion economy, the role of mining in ensuring raw material security and self-reliance is more crucial than ever.

This paper examines the current state of Indian mining, highlighting key resources, policy reforms, technological adoption, and sustainability initiatives. It also evaluates the emerging importance of critical minerals like lithium and rare earths in the context of India's clean energy transition. With recent policy shifts, strategic international collaborations, and the integration of digital technologies, India is poised to unlock the full potential of its mining industry. The paper concludes with a future outlook emphasizing the need for responsible, inclusive, and green mining practices to align with national goals of self-reliance and sustainable development.

Keywords: Green Mining, GVA, Critical Minerals, MMDR Act, Mineral Production and Self Reliance.

INTRODUCTION

Mining sector is an important segment of the Indian economy. Since independence there has been a pronounced growth in the mineral production both in terms of quantity and value. As on now, India produces as many as 95 minerals, which include 4 fuels, 10 metallic, 23 non-metallic, 3 atomic and 55 minor minerals (including building stones and other materials).

Immediately after independence in 1947 and with the

adoption of Industrial Policy Resolution, the search for minerals particularly for those essential to industrial development was intensified. Ambitious programmes were launched in successive 'Five Years Plans' to increase the production of minerals to meet the growing demand of the core industries like steel, cement, power, non-ferrous metals, fertilizer, etc. and also in view of higher exports for much needed foreign exchange. Government of India initiated major economic reforms in 1991 aimed at deregulation and de-licensing of the existing regime. In tune with this, a new era was ushered in when the National Mineral Policy was pronounced in March 1993 and the mining sector was opened up for private initiative and investment. To give further fillip, the new National Mineral Policy 2008 replacing the 1993 mineral policy came into force in March 2008. The National Mineral Exploration Policy (NMEP) for non-fuel and non-coal minerals was spelt out in 2016 to have strategy and outline the action plan that would be adopted to ensure comprehensive exploration of country's mineral resources. Later on, the new National Mineral Policy 2019 replacing the extant National Mineral Policy 2008 was pronounced in February 2019 to have a more effective, meaningful and implementable policy that brings in further transparency, better regulation and enforcement, balanced social and economic growth as well as sustainable mining practices.

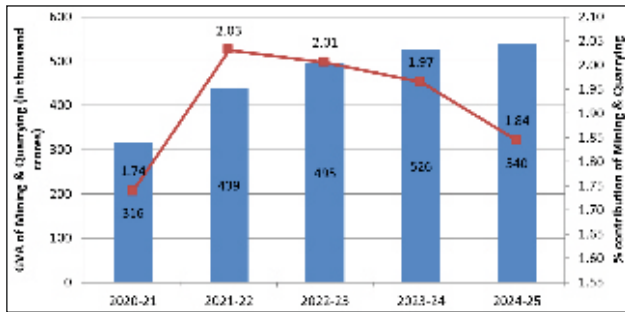
Cascading reforms in the form of Mines & Minerals (Development & Regulation) Act 1957 and Rules made there under are made from time to time to give effect to the policy directives. Key reforms have been undertaken through amendments in the MMDR Act in 2015, 2020 and 2021. The reforms are expected to show positive results so as to achieve self-reliance as envisaged in "Make in India" objectives. Further, looking into the vision for clean energy and to ensure supply chain of critical minerals, National Critical Mineral Mission with an outlay of 34,300 crore has been launched by the Government of India.

PRESENT SCENARIO OF INDIAN MINING INDUSTRY

Domestic Scenario

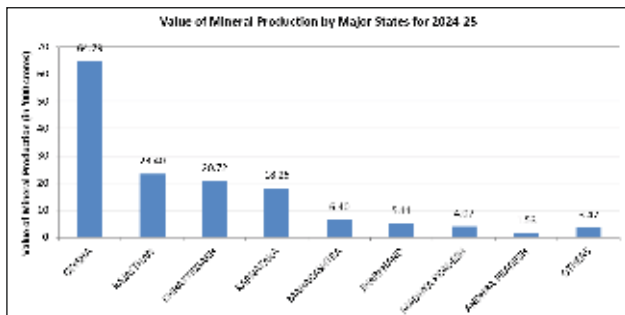
The Gross Value Added (GVA) from India's mining & quarrying sector reached approximately 5.40 lakh crore

at current prices in the fiscal year 2024–25, accounting for about 1.80 % of India's GDP. On a constant price basis (2011–12), its contribution was 3.39 lakh crore, representing around 1.97 % of total GVA. While the mining sector remains a modest but vital contributor (~2 % of GDP), its steady growth in real terms underscores its significance within India's industrial and infrastructural development.



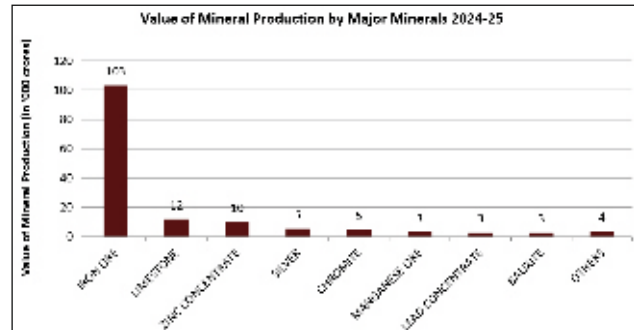
The provisional total value of mineral production (excluding atomic, fuel, and minor minerals) for 2024-25 is estimated at ₹ 1,47,723 crore, marking a growth of 5.2% over the previous year. Metallic minerals dominate this value, with a provisional estimate of ₹ 1,34,462 crore, contributing 91.02% of the total. In contrast, the value of non-metallic minerals stands at ₹ 13,261 crore, or 8.98%, underscoring the importance of metallic minerals in the overall production landscape.

The Odisha emerged as the leading state, contributing ₹ 64,785 crore, representing 43.9% of the country's total. In this sequence, the Rajasthan, Chhattisgarh and Karnataka also played a significant roles, with contributions of ₹ 23,399 crore (15.8%), ₹ 20,724 crore (14%), and ₹ 18,248 crore (12.4%), respectively. The Maharashtra and Jharkhand added ₹ 6,395 crore (4.3%) and ₹ 5,105 crore (3.5%), further illustrating the diverse contributions of key states to India's mineral production in 2024-25(P).



The provisional value of metallic minerals in 2024-25 stood at ₹ 1,34,462 crore, reflecting a growth of 5.6% compared to the previous year. Whereas, the provisional value of non-metallic mineral production stood at ₹ 13,261 crore, marking a modest 0.7% increase over the previous year. The iron ore remained the largest contributor, accounting for ₹ 1,03,316 crore or 69.94% of the total value, followed

by limestone at ₹ 11,864 crore (8.03%), zinc concentrate at ₹ 10,009 crore (6.78%), silver at ₹ 5,478 crore (3.71%), and chromite at ₹ 4,556 crore (3.08%).



In terms of production, bauxite reached to 24.71 million tonnes, marking a slight increment of 3.1%. Chromite production reached to 3.03 million tonnes, reflecting a 3.9% decrease. Copper concentrate production declined by 16% to 105 thousand tonnes, while primary gold production saw 2.8% rise and reached to 1,627 kg. Iron ore production reached to 289.4 million tonnes, a 4.6% increase. The lead concentrate production was 392.6 thousand tonnes, with a 3.1% growth and zinc concentrate production increased by modest 0.7% to 1,721.6 thousand tonnes. Manganese ore production also saw a surge, rising by 12.4% to 3.8 million tonnes.

The country's Public sector contributes to more than 90% of production of copper ore, Tin and Gold. On the other hand, Private sector contributes almost 100% in production of Lead & Zinc ore and concentrates.

India's Global Position and Ranking

India sits firmly among the world's leading mineral-rich nations, boasting reserves and production of over 95 mineral types including fuel, metallic, non metallic, atomic, and minor minerals. The country holds large reserves of iron ore contributing 2.89 % ranked 7th globally, followed by graphite at 3.07% (7th rank), chromite at 14.11 % (3rd rank), manganese at 1.79% 7th rank) and bauxite at 2.16 % (8th rank).

India ranks among the top mineral-producing nations in the world trailing behind China, the USA, Russia, and Australia with a total annual output nearing of 148 billion. In the non-ferrous sector, India is the 3rd largest global producer of aluminum and consistently places among the top 6 producers of Bauxite. The nation's production of iron ore reached a record 289 million tonnes in FY 2024–25, firmly positioning it as the 3rd largest producer worldwide, while chromite at 3rd position, manganese at 5th position and chromite at 3rd position, reported a robust and consistent growth.

The country also holds significant positions in lime and other industrial minerals, such as limestone enhancing its profile in global supply chains. These rankings reflect India's extensive

mining footprint, supporting strong growth across energy, infrastructure, construction, automobile, and technology sectors.

Self-Reliance in Minerals

India's ambition to become a globally competitive economy hinges significantly on achieving self-reliance in mineral resources. As a nation endowed with a rich geological landscape, India continued to be wholly or largely self-sufficient in most of the industrial minerals. These are primary raw materials for many industries, such as, iron & steel, aluminium, cement, refractories, ceramics, glass etc. India is self-sufficient or near to self-sufficient in bauxite, chromite, iron ore and limestone. India is deficient in kyanite, magnesite, rock phosphate, manganese ore, etc. and the demands of these are mostly met by imports.

In spite of significant production, some ores/minerals are also imported to meet the demand either for blending with locally available mineral raw materials and/or for manufacturing special qualities of mineral-based products. To meet the increasing demand of uncut diamonds, emerald and other precious & semi-precious stones by the domestic cutting and polishing Industry, India is dependent on imports of raw uncut stones for their value-added re-exports. The degree of self-sufficiency in respect of various principal minerals in 2023-24(P) is as below:

Degree of Self-sufficiency in Principal Minerals, 2023-24(P)

Sl. No.	Ores / Minerals	Apparent Demand* ('000 tonnes)	Production/ Domestic Supply ('000 tonnes)	Degree of Self-sufficiency (%)
1	Bauxite	28296	23968	85%
2	Chromite	3318	3148	95%
3	Iron ore	235336	276752	100%
4	Kyanite	4.82	3.32	69%
5	Limestone	484156	452009	93%
6	Magnesite	608	132	22%
7	Manganese ore	8974	3381	38%
8	Rock phosphate (including apatite)	10368	1558	15%

Figures rounded off

P: Provisional.

Source: MCDR Returns for production data and DGCI&S for export & import data.

*: Apparent demand (production + import-export)

INDIAN MINERAL SECTOR- FUTURE OUTLOOK WITH SWOT ANALYSIS.

Taking into account the present scenario and envisaged reforms & initiatives, an attempt has been made to look future outlook of Indian mineral industry through SWOT analysis.

Strengths

1. Abundant Mineral Resources

India has a rich endowment of metallic and non-metallic mineral resources, which forms the backbone of its industrial economy. The country is among the top producers of iron ore, bauxite, chromite, manganese, limestone etc. These resources are essential for the steel, aluminum, cement, and infrastructure sectors. India's vast geological diversity from the peninsular shield regions to sedimentary basins ensures a steady potential for new mineral discoveries. With mineral-rich states like Odisha, Chhattisgarh, Rajasthan, Jharkhand, etc hosting some of the world's largest deposits, India enjoys a competitive advantage in securing raw materials for its expanding manufacturing and construction base.

2. Strategic Geographical Advantage

India's geographical location offers strategic access to both Asian and global markets. Mineral-rich eastern and central India is well-positioned to supply nearby ASEAN countries, the Middle East, and even Africa. About 11,000 km long coastline and impressive port infrastructure of country can facilitate efficient mineral exports. The country's proximity to emerging industrial hubs in Southeast Asia increases its relevance as a supplier of raw and semi-processed minerals and mineral based products.

3. Policy Support & Reforms

India's mineral policy landscape has undergone transformative shifts since 2015 aimed at boosting transparency, sustainability, and resource security. The MMDR Amendment Act, 2015 ushered in a mandatory auction system for mineral concessions, replaced discretionary allocations, extended lease terms to 50 years, and established the National Mineral Exploration Trust (NMET) and District Mineral Foundation (DMF) to fund exploration and community development. Building on this, the 2021 MMDR Amendment further eased business operations by allowing private and foreign entities to hold composite prospecting-cum-mining licences (CEMP) and removing end-use restrictions on coal, while enhancing transparency and enforceability. Complementing legislative changes, the National Mineral Policy 2019 promoted scientific methods, infrastructure investment, R&D support, value addition through beneficiation, and reclamation practices under inter-generational equity frameworks.

In response to evolving global demands and strategic vulnerabilities, India has recently stepped up reforms focused on critical and strategic minerals. The National Critical Minerals Mission (NCMM), launched in early 2025 with 34,300 crore, aims to accelerate domestic exploration, processing, recycling, and overseas acquisition of key minerals like lithium, cobalt, nickel, and rare earth elements. The MMDR Amendment Act, 2023 empowers the government to auction critical mineral blocks, introduces a tailings policy, and adjusts royalty rates to incentivize extraction from waste materials. Additionally,

customs duty exemptions and reclassification of certain minerals from 'minor' to 'major' have been introduced to ease investment barriers. These initiatives, alongside India's inclusion in the Minerals Security Partnership, form a robust framework aimed at achieving self-reliance in strategic minerals while adhering to ESG norms.

4. Growing Domestic Demand

India's ambitious goals for infrastructure development, urbanization, and industrial expansion are driving a significant increase in mineral demand. The steel and aluminum industries, supported by the National Infrastructure Pipeline (NIP) and programs like "Make in India," require large-scale mining of iron ore and bauxite. Cement production, construction materials, and non-metallic minerals like limestone and gypsum are in constant demand due to real estate and public works expansion. Additionally, emerging sectors such as electric vehicles, renewable energy, and electronics manufacturing are generating new demand for lithium, copper, graphite, and rare earths, ensuring sustained long-term growth in mineral consumption.

5. Large Labor Pool & Mining Expertise

India has a large pool of skilled and semi-skilled labour with experience in traditional and modern mining practices. Public and private sector companies like NMDC, Hindustan Zinc Limited, SAIL, and OMC have decades of operational expertise. Educational institutions supply trained professionals in geology, mining engineering, and metallurgy. With a workforce familiar with diverse geological settings and mining techniques, India is positioned to scale mining activities with relatively lower labour costs compared to developed nations. This expertise enables rapid mobilization of resources, operational resilience, and the potential for adopting new technologies in the mining value chain.

Weaknesses

1. Import Dependence on Certain Minerals

Despite having vast mineral resources, India remains highly dependent on imports for several critical and strategic minerals, especially copper ore, lithium, cobalt, and rare earth elements (REEs). The lack of lithium and cobalt refining capabilities forces India to import finished battery components. This dependency increases the country's vulnerability to global supply chain disruptions, price volatility, and geopolitical tensions. Without significant investments in exploration and processing infrastructure, India's import reliance will continue to pose economic and strategic risks.

2. Out-dated Mining Techniques in Small Mines

A large portion of India's mining operations, especially in the small and medium-sized segment (SMEs), still relies on manual or semi-mechanized mining methods. This results in low productivity, high wastage of resources, and increased operational hazards. Inadequate use of advanced

equipment and lack of digital systems limit the efficiency of these mines. Small miners often face financial constraints in adopting automation, leading to a technological divide between large corporate miners and smaller players. These outdated practices increase operational costs, lower yields, and pose significant safety and environmental risks, limiting the overall competitiveness of the sector.

3. Infrastructure Bottlenecks

The India faces significant infrastructure constraints in the mining sector, particularly in mineral transportation. Many mining regions in eastern and central India lack adequate rail and road connectivity to ports and processing centres. This results in logistics bottlenecks, higher transportation costs, and time delays, reducing India's ability to compete globally in mineral exports. Ports require expansion and modernization to handle bulk mineral shipments efficiently. Additionally, the absence of dedicated mineral corridors, slurry pipelines, and evacuation networks continues to hamper large-scale mining operations. These logistical challenges lead to underutilization of mining potential and discourage investment in remote mineral-rich areas.

4. Environmental & Social Challenges

The Mining operations in India often encounter land acquisition issues, displacement of communities, and environmental litigation. Projects face resistance from local populations concerned about loss of livelihood, ecological damage, and inadequate compensation. Mining in forest areas or eco-sensitive zones leads to regulatory delays and legal disputes. Rehabilitation and Resettlement (R&R) policies, though mandatory, are sometimes poorly implemented, leading to conflicts and social unrest. In addition, illegal mining activities in some regions cause environmental degradation, groundwater depletion, and pollution, further tarnishing the industry's image. These challenges affect project timelines, escalate costs, and impact the social license to operate.

5. Exploration Deficit

India has only explored about 30% of Obvious Geological Potential, leaving large tracts of resource-rich land unexplored or under-explored. The country's exploration agencies have limitations in terms of manpower and technology to conduct large-scale mineral prospecting. Private sector exploration is still at a nascent stage due to historical policy constraints, though recent reforms are opening new avenues. Without extensive exploration, India is missing out on discovering new deposits of base metals, battery minerals, and rare earth elements, resulting in lost opportunities for economic development and strategic security.

Opportunities

1. Critical Mineral Demand Surge

The global shift toward electric mobility, renewable energy, and high-tech manufacturing has triggered a surge in demand for critical minerals, including lithium, cobalt,

nickel, graphite, copper, and rare earths. India, aiming to reduce its import dependence and become a manufacturing hub for batteries and electronics, has a unique opportunity to develop its domestic critical mineral ecosystem. The Geological Survey of India has already identified lithium and REE reserves, and new mineral block auctions are underway. By tapping into these resources, India can secure raw materials for its energy transition goals and defense sector requirements, fostering economic and strategic resilience.

2. Value Addition Focus

There is a growing policy emphasis on shifting from raw mineral extraction to downstream processing and value addition. Instead of exporting low-value ores, India is promoting the development of beneficiation plants, smelters, and alloy manufacturing units. For example, converting bauxite into aluminum or refining zinc and copper domestically generates higher employment, tax revenues, and industrial growth. This approach aligns with India's vision of becoming self-reliant in metals production, reducing foreign exchange outflow, and encouraging local manufacturing under initiatives like Atmanirbhar Bharat. It also helps India move up the global supply chain from being just a raw material supplier.

3. Technological Modernization

The Indian mining sector is witnessing a technological transformation with the adoption of AI, drones, 3D mapping, and predictive analytics. These technologies improve resource estimation, mine planning, and operational efficiency. Automation of drilling, hauling, and ore processing reduces human error and enhances safety. Digital twin technology, remote monitoring, and real-time data analytics enable better decision-making. Smart mines also lead to optimized resource utilization and lower environmental footprints. With global mining leaders already implementing these technologies, India's mining sector can leapfrog traditional limitations by embracing innovation, making its operations more productive and globally competitive.

4. International Collaborations

To strengthen mineral security and promote self-reliance in critical and strategic minerals, the Ministry of Mines has established a joint venture company named Khanij Bidesh India Ltd. (KABIL). The primary mandate of KABIL is to acquire mineral assets abroad, focusing specifically on securing supplies of critical and strategic minerals for India.

On 15th January 2024, KABIL entered into an Exploration and Development Agreement with CAMYEN, the state-owned mining company of Catamarca province, Argentina, for the exploration and mining of five lithium blocks in Argentina. Additionally, KABIL has signed a Memorandum of Understanding (MoU) with the Critical Mineral Facilitation Office (CMFO), under the Department of Industry, Science and Resources (DISER), Government of

Australia. This MoU aims to facilitate joint due diligence and potential collaborative investments in lithium and cobalt assets in Australia.

The Ministry of Mines is actively participating in several international collaborations and multilateral initiatives aimed at strengthening India's role in the critical minerals and clean energy supply chain. These include engagements with the Minerals Security Partnership (MSP), the Indo-Pacific Economic Framework (IPEF), the U.S.–India Initiative on Critical and Emerging Technology (iCET), and the UN Secretary General's Panel on Critical Energy Transition Minerals, among others.

5. New Exploration Models

The recent liberalization of India's exploration policy allows for private sector participation in mineral exploration, including auction-based revenue-sharing models and composite licenses that combine exploration, prospecting, and mining. The establishment of the National Mineral Exploration Trust (NMET) provides dedicated funds for exploration activities, improving access to modern survey technologies like aerial geophysical mapping and satellite imagery. By encouraging exploration in under-explored areas and deploying cutting-edge technology, India can unlock new mineral deposits, create jobs, and ensure long-term supply security for its industries.

The MMDR Amendment Act, 2021 introduced provisions allowing private entities to undertake mineral exploration without the need for a prospecting license. To promote greater private sector involvement in exploration, the government has so far recognized 32 private agencies as Notified Private Exploration Agencies (NPEAs). These agencies are currently engaged in exploration projects, with financial support provided through the National Mineral Exploration Trust (NMET).

The Ministry of Mines is prioritizing the exploration of critical and strategic minerals, with NMET actively funding related projects across various exploration agencies. To further encourage and incentivize private sector participation in mineral exploration—particularly for critical, strategic, and deep-seated minerals—the Ministry has launched two schemes for partial reimbursement of exploration expenses. Under these schemes, holders of Composite Licences and Exploration Licences are eligible for reimbursement of up to 50% of the exploration costs they incur.

6. Sustainable Mineral Development

Indian mineral sector has adopted a concept of Star Rating Evaluation of mines. Under the Star Rating Scheme, a credible system of evaluation of mining footprints and to take up mining activity, encompassing inclusive growth, without adversely affecting the social, economic and environmental well being has been developed. It has been instituted as a two-tier system providing self-evaluation templates to be filled in by the mine operator in online system developed through IBM portal followed by

validation through IBM. This has been mandated through statutes. The commissioning and implementation of concept of Star Rating system has paved a path for sustainable mineral development keeping in view the global Sustainable Development Goals.

Threats

1. Global Competition for Critical Minerals

China dominates the global supply chain for rare earth elements, lithium refining, and battery metals, controlling nearly 70–80% of global processing capacity. This poses a significant threat to India's ambitions in critical minerals. Countries worldwide are competing for limited supplies of strategic resources, leading to price wars, resource nationalism, and geopolitical competition. India faces challenges in acquiring stakes in overseas mines due to competition from wealthier countries with established global mining giants. Without rapid capacity building, India risks being marginalized in the critical mineral race, affecting its clean energy and electronics manufacturing goals.

2. Environmental Regulations and Litigation

Mining operations in India are increasingly subject to environmental activism, judicial interventions, and regulatory scrutiny. Several projects have been delayed or cancelled due to violations of environmental norms or lack of proper community consultation. Strict regulatory regimes, while essential for ecological balance, can result in prolonged delays, litigation costs, and investor uncertainty. The balance between mining development and environmental protection is delicate, and failure to maintain this balance can lead to reputational risks, license cancellations, and policy reversals.

3. Commodity Price Volatility

The mining sector is inherently exposed to global commodity price fluctuations. Prices of metals are determined by international markets. Demand-supply imbalances, geopolitical tensions, or economic slowdowns can lead to sudden drops in mineral prices, affecting profitability. For India, where mining investments often have long gestation periods, such volatility can disrupt project economics, delay expansions, and deter new investments. This unpredictability in pricing makes it difficult to plan large-scale capital investments confidently.

4. Import Competition

India's domestic mineral and metal producers face competition from cheaper imports of processed minerals and metals, particularly from China, Indonesia, and other Southeast Asian nations. Dumping of low-cost alloys, aluminum products, and copper cathodes into the Indian market affects the profitability of local industries. Without protective tariffs, anti-dumping measures, or incentives for domestic production, Indian miners and processors may struggle to remain competitive, risking job losses and closures of local industries.

5. Climate Change & Environmental, Social, and Governance (ESG) Pressure

The mining sector globally is under increasing pressure to align with climate change goals, such as net-zero emissions by mid-century. Mining is energy-intensive and contributes to carbon emissions, making it a target for stricter climate regulations. Failure to transition to low-carbon mining operations may lead to penalties, loss of international investors, and limited access to sustainable finance. Additionally, global financial institutions and fund managers are now prioritizing ESG compliance, and Indian mining companies will need to adapt rapidly to meet these expectations or risk losing access to global capital markets.

CONCLUSION

India's mining sector stands at a defining juncture, with an expanding role in economic growth, resource security, and global competitiveness. Over the past decade, significant reforms such as auction-based allocation, critical mineral prioritization, and simplified licensing have unlocked private investment and laid the groundwork for sustainable development. Technological integration in mining and exploration, including artificial intelligence, machine learning, drones and IoT can revolutionize exploration, improve safety, and enhance productivity. These technological advancements are gradually being adopted by major players, it is signalling a shift toward modern, efficient operations. Environmental sustainability and community welfare are increasingly emphasized through green mining initiatives, stricter ESG protocols, and the effective deployment of District Mineral Foundations across mining regions.

Looking ahead, the sector's future is shaped by global clean energy demands and India's quest for mineral self-reliance. This would require a quantum leap in exploration, licensing, production, and exports. Domestic demand for minerals is expected to grow rapidly due to rising infrastructure projects, urbanization, manufacturing under Make in India, and the clean energy transition. There is also potential for India to become a global processing and refining hub, especially for rare earths and battery minerals. Public-private partnerships, stable policies, and effective regulatory mechanisms will be critical to achieving these goals.

Many States like Odisha, Karnataka, Madhya Pradesh, Chhattisgarh, Rajasthan etc. are raising production targets while procedural reforms, including online mining plans and faster clearances, are improving efficiency. The National Infrastructure Pipeline (NIP) and Gati Shakti scheme offer an opportunity to integrate mining infrastructure with national development goals. As India strives to meet its production goals and environmental commitments, the rallying cry of "responsible, inclusive, and future-ready mining" will define its trajectory. With policy momentum, technological innovation, and stakeholder collaboration, Indian mining can emerge as a key pillar in the nation's journey toward a resilient and green economy.



Present Scenario and Future Perspective of Mining in Jammu and Kashmir, India.

Dr. Raj Kumar

Deputy Director

Geology and Mining Department, J&K.

Abstract

An attempt has been made to study the “Present Scenario and Future Perspective of Mining in J&K, India”. Although, the mining is the most important economic activity next to agriculture. It provides not only employment in Remote and Tribal areas apart from generating revenue and economic activities in area where minerals occur. Being Major contributor to GDP it also plays a significant role for the establishment of mineral based industries. Mining thus provides backward and forwarded linkages in the economy more than any other sector in making available raw materials for more spectrums of products. In Jammu and Kashmir mining leases of major as well as minor minerals have been granted for “Captive” and “Non-Captive” purposes. The Mining is being conducted with open cast methods for the extraction of the minerals like Limestone, Gypsum, and various other minerals, the leases of which were granted by the Government of India as well as Jammu and Kashmir. In J&K coal mining is being conducted by way of underground mining.

In Jammu and Kashmir 36 number of leases of in-situ Major Mineral like limestone and 24 in-situ Minor Mineral gypsum have been granted. It is to mention that 23 limestone leases have been granted in Anantnag District alone whereas, 09 in District Pulwama, 03 in District Srinagar of Kashmir Division and one in District Poonch of Jammu division. Out of 36 number of Limestone leases granted by the Department 05 number of leases are operational and 31 numbers are non-operational. Similarly out of 24 mining leases of Gypsum 15 number of leases alone has been granted in Baramulla District of Kashmir division out of which 07 are operational whereas 08 are non-operational due the interference of JKEIAA and NGT with regard to falling lease area within 01 kilometer radius from Eco-sensitive zone. In Doda District of Jammu Division 06 gypsum leases have been granted out of which 01 is operational and 05 are non-operational. Similarly there are only 03 Gypsum leases granted in the Ramban district of Jammu division out of which only 01 lease at Perlanka area of the district is operational. The material from the above leased out area is being exploited by semi-mechanized

methods by open cast mining. The Coal deposits have been explored by Department of Geology and Mining and at some places by Geological Survey of India in Jammu division are being exploited by underground mining by the Jammu and Kashmir Minerals Ltd. a Corporation of Government of Jammu and Kashmir. About 1.5 million tonnes of coal has been produced from these mines/areas so far, as reported by the J&KML. Besides reserves to the tune of 09 million tonnes of Lignite have been explored in Nichahom and adjoining areas of Handwara Tehsil, District Kupwara of Kashmir Division.

It is imperative to mention that the Minor Mineral Blocks of River Bed, Material (RBM) have also been e-auctioned after the Amendment of the Minor Mineral Concession Rules issued vide SRO 105 dated 31-03-2026 and NGT Guide lines of 2016 and 2020. Accordingly, 225 Minor Mineral Blocks were e-auctioned out of which 207 leases were granted by the department, 137 in Jammu Division and 70 in Kashmir Division. Quarry Licenses 31 number were also been granted and out of which 17 quarries are operational as on date.

Economic Importance, Mineral Production, Policy Reforms, Technological Adoption, Environmental Concerns, Global Ranking, Market Size and Growth, Challenges, Strategic Importance, Economic Contribution and social Considerations are the main factors which have key role in the present scenario of Indian Mining.

The Sustainable and Responsible Mining, Technological Transformation, Circular Economy, Strategic Reforms, Global Leadership, Private Sector Participation, Water Management, Technological Innovation, Automation and Robotic, Rehabilitation of Mined Area, Growth Potential, Focus on Sustainable Practices, Critical Minerals, and Community Engagement are most important factors which has significant role in future perspective of Indian mining to achieve the heights to become the third largest Economy of the world.

The mining sector is contributing in the GDP and economy of our country by providing direct or indirect employment opportunities to unemployed youths. There is a lot of scope

of mining in the country which will definitely play a significant role for the establishment of Mineral based Industries, if mining is being done with care of environment degradation, sustainable and people friendly atmosphere. If mineral wealth is not conserved for future generation, there may be not only financial loss to the country but we will lose our mineral resources too. It is the right moment to use them judiciously and conserve our mineral wealth besides to work out other sources in place of minerals for revenue realization like manufacturing of War Weapons, Machinery/equipments, Medicines and other day to day required items which can be exported to other countries.

Introduction:

The department of Geology and Mining J&K came into existence in the year 1960 and since then it has been engaged in exploration of mineral wealth of Jammu and Kashmir. It has made utmost efforts to explore various minerals like Limestone, Gypsum, Bauxite, Marble, Quartzite, Dolomite besides decorative stones i.e. Granite, Slate, Marble, fuels minerals like Coal, Lignite, Graphite and Sapphire a World famous Gem stone. It is imperative to mention that the explored minerals (Major/Minor/Gem Stone) were leased out to various entrepreneurs like Government Corporations and Private sectors not only from J&K but from all over India. The extracted minerals are not only the source for the establishment of mineral based industries but contributing a lot to the Government Exchequer and providing job opportunities to millions.

Amendments in Rules:

It is to mention that with the Amendments in MM(D&R) Act 1957 and issuance of Mines and Minerals Concession Rules and SRO 105 dated 31-03-2016 it became mandatory to grant of Mining Leases of Major as well as Minor Minerals through e-auction mode. In Jammu and Kashmir the Directorate of Geology and Mining had made attempt wherein more than 225 Minor Mineral Blocks were e-auctioned and out of them 207 Mining Leases of Minor Mineral were granted and the Blocks were made operational following the Sand Mining Guidelines 2016 and 2020 besides all other Environmental conditions laid down by JKEIAA and Pollution Control Department.

All the leases are made operational with Open Cast Methods of Mining with using semi Mechanized methods and techniques. The conditions laid down while grant of Environmental Clearance (EC) and Consent to Operate (CTO) by the concerned Authorities were followed by the Department in letter and spirit. In Jammu and Kashmir the entire mineral deposits whether Major or Minor Minerals are extracted (Exploited) with open cast Mining except Coal in and around Kalakot area of District Rajouri and Reasi and Sapphires Gem Stone of Padder area of District Kishtwar.

Major Mineral (Limestone) Mining:

In Jammu and Kashmir 36 number of leases of in-situ Major Mineral limestone have been granted to Government as well as private Sector. It is to mention that 23 limestone mining leases have been granted in Anantnag District alone whereas, 09 in District Pulwama, 03 in District Srinagar of Kashmir Division and one Mining Lease of limestone in District Poonch of Jammu Division. Out of 36 number of Limestone leases granted by the Department 05 number of leases are operational and 31 numbers are non-operational due to the one reason or the other. The Department has made utmost efforts to make these leases operational. It is to mention that the limestone is being exploited (Extracted) by open cast methods of Mining with using drilling and blasting techniques.

Minor Mineral (Gypsum) Mining:

In Jammu and Kashmir 24 Nos. of Mining Leases of the Gypsum deposit were granted by the Geology and Mining Department and the mining is being done by open cast methods with using drilling and blasting techniques. Similarly out of 24 mining leases of Gypsum 15 number of leases alone has been granted in Baramulla District of Kashmir division out of which 07 are operational whereas 08 are non-operational due the interference of Forest Department and JKEIAA with regard to falling lease area within 01 kilometer radius from Eco-sensitive zone. In Doda District of Jammu Division 06 gypsum leases have been granted out of which 01 is operational and 05 are non-operational as on date. Similarly there are only 03 Gypsum leases granted in the Ramban district of Jammu division out of which only 01 lease at Perlanka area of the district is operational. The material from the above leased out area is being exploited by semi-mechanized methods by open cast mining.

Coal (Fuel Mineral) Mining:

The occurrence of coal seams of Eocene age in Jammu region is reported at Kalakot, Metka, Badough, Dali, Mahogla, Beryal, Kotla, Chakkar, Magal, Jangalgalli, Sukhwalgalli areas of District Rajouri, Reasi and Udhampur even traces in District Ramban. The investigation of the coal was conducted by various departments even before independence. On the basis of the exploration and reserve estimation by the exploring departments/Geoscientists, a thermal plant was established at Kalakot. The area was explored extensively in and around Kalakot and other above mentioned areas. The exploitation of the deposits was made by M/s. JK Mineral Ltd. by way of establishment of underground mines, whereas only Chakker area where the coal was exploited by open cast methods of mining. The coal is of Bituminous to Semi-Anthracitic in nature and occurs as pinching and swelling in three to four seams of variable thickness ranges from few inches to 1.5 meters which shows inconsistent and erratic behaviour.

The coal mines were established by M/s. JK Minerals Ltd. in Kalakot and adjoining areas of District Rajouri at Jigni, Tatapani, Beragoa, Sair, Dali, Badough, Metka, Old and New Mahogla. Beryal, Kotla, Chakkar and Jangalgali areas of District Reasi. The status of each coal mine is given as under:

a) Jigni Coal Mine:

As per data provided by the JK Minerals Ltd. and ground verification, the Jigni coal mine having coordinates N 33°14'56", E 74°21'45" was established at 885 meters a m s l in the year 1970-71 to exploit the coal deposit of upper coal measures (UCM). In all five inclines were driven having maximum length up to 300 meters. The bed rock gradient is 1:2 in the mine and there was gas problem in them. The mine was closed in the year 1994 by the JK Minerals Ltd. due to exhaust of coal deposit and pinching behavior of the coal seams.

b) Tata Pani Coal Mine:

Tata Pani Coal Mine having coordinates N 33°14'24", E 74°24'48" was established at 832 meters a m s l in the year 1970-71. Six inclines were driven in the Tata Pani area having maximum length of 360 meters. The coal deposit exploited is of upper coal measures (UCM). The coal mine was closed in the year 1994 on exhaust of the coal deposit. The coal mine was closed due to pinching behaviour of coal seams and exhaust of the coal deposit since all the six inclines were driven from one end to another across the hillock.

c) Beragoa Coal Mine:

The coal mine was established in the year 1961-62 at an altitude of 842 meters having coordinates N 33°13'40.3" and E 74°24'4" wherein four inclines were driven having maximum length up to 440 meters. The coal exploited from Beragoa coal mine was of lower coal seam (LCM). The roof rocks were good and competent enough to bear the load. Total production obtained from the Beragoa, Sair and Dali coal mines is 3, 74, 701 tonnes as per record provided by JK Minerals Ltd. and the coal mines were closed in the year 1998 after completion of depillaring.

d) Sair Coal Mine:

The Sair coal mine having coordinates N 43°12'43.3", E 74°25'14.4" was established at 700 meters a m s l near Sairi Tawi at Kalakote, District Rajouri in the year 1963. Two inclines were driven having length 70 and 50 meters. The bed rock gradient is 1:2 whereas the roof rocks are very poor and crumbled. The incline driven in the Sairi Tawi was most productive and was closed on the exhaust of the coal deposit. The incline No. 2 at Sair along the Sairi Tawi has poor roof rocks and was driven up to 50 meters. On physical verification it has been observed that initial face of the incline has been concreted wherein the whole mine is filled with water since, it is established along the Sairi Tawi. The coal seam exploited is of upper coal measures (UCM)

and the mine was closed in the year 1980 due to high make of water.

e) Dali Coal Mine:

The Dali coal mine was established at 840 meters a m s l in the year 1963 having coordinates N 33°13'42.3", E 74°25'33.8". In the area 05 Nos. of inclines were driven from where coal of upper coal measures (UCM) was exploited. The coal deposit has low Carbon % whereas it has high percentage of ash even some samples have shown more than 60%. The coal mine have poor roof rocks whereas the bed rock gradient is 1:2 over which the coal mine has been established. The mine was closed in the year 1980 on the basis of pinching of the coal seams in extension as reported by JK Minerals Ltd.

f) Badough Coal Mine:

It is to mention that the Department of Geology and Mining has explored the Badough area in extension of the already abandoned old coal mine during 1983-84 to 1989-90 and divided the area into three sub-blocks "D", "E" and "F" wherein 2237.64 metres of drilling and 37 metres of stone drivage was conducted to establish the presence of coal seams. The report reveals that there are two types of coal horizon upper coal measures (UCM) and lower coal measures (LCM). The coal seams of upper coal measures are shaley and friable in nature where as the coal seam of the lower coal measures is bituminous to semi-anthracitic in nature having good percentage of Carbon Content. It is pertinent to mention that the roof rocks are sandy shale having thickness from 1.35 m to 9.0 m whereas the floor is covered with Breccia which is hard and feasible to be treated as floor of the mine. Probable Geological Reserves in the above said explored area of Badough are reported to be 20,500 tons. The JK Minerals Ltd. has started New Coal Mine in the above said explored area of Badough wherein two inclines have been driven and the mine has been developed up to 60 meters whereas, only 1,026 tons of the deposit has been exploited so far.

g) Metka Coal Mine:

The Metka coal mine was established in the year 1961-62 at an altitude of 826 meters by JK Minerals Ltd. wherein 21 inclines were driven having maximum length 770 meters. The bed rock has 1:2 gradient and the coal seam exploited is of upper coal measures (UCM) since the lower coal seam has not been reported in the exploration conducted by the Geology and Mining Department and Geological Survey of India (GSI) wherein more than 65 exploratory boreholes were drilled to determine the subsurface behaviour and consistency of the coal seams in the area. The mine is located at and around the coordinates N 33°30'5.2", E 74°27'38.5". The total production achieved by the JK Minerals Ltd. up to 2016-17 is 3, 64, 903 tons. It is pertinent to mention that the JK Minerals Ltd. has submitted mine Closer Plan to the Coal Controller, Ministry of Coal, Kolkata

vide letter No Agent (KLK)/Camp Jmu/2016/532 dated 29-10-2016 on the ground that the coal mining in the said mine area has been carried out for more than 50 years.

h) Old Mahogla Coal Mine:

In Old Mahogla area the mine was established in the year 1984-85 around coordinates N 33°12'27.1", E 74°29'15.5" wherein 03 inclines were driven up to the maximum extent of 140 meters. The gradient of the bed rock is 1:2 over which the inclines were driven in the Northern limb of the Mahogla inlier. The mine was closed in the year 1991 due to collapse of roof rocks due to which the mine could not be taken up further. No separate record of production of coal is available.

It is pertinent to mention that in the old Mahogla having two inclines at coordinate N 33°12'19.5", E 74°29'21.9" at an altitude 741 meters were driven up to 20 m and 12 meters wherein the coal of the bottom seam of the lower coal measures (LCM) was touched in one of the incline whereas in the second drive which was developed up to 12 meters coal was not encountered. Further, the department has explored the area in extension during year 2012-2018 by way of Detailed Geological Mapping more than 7 lac Sq. Mts with drilling of 11 boreholes, where encouraging results were not found.

i) New Mahogla Coal Mine:

The coal mine of New Mahogla area was established in the year 1984-85 and 07 nos. of inclines were driven. In the new Mahogla incline No. 1-3 were driven in the northern limb of the Mahogla inlier whereas the incline No. 4-7 were driven in the southern limb of the inlier. The Great Limestone is exposed at the base where as the coal mines are established on the both the side of the limbs. Total combined dispatch of Old Mahogla and New Mahogla coal mines upto 2017 were 2,49,199 tons. The Geology and Mining Department has explored the area by way of drilling on the requisition of JK Minerals Ltd. a premier Corporation engaged in Mining and the lower coal seam having thickness of 2 10 and 2 was encountered in two exploratory boreholes. The southern faces of the incline No. 3 can be taken up for the exploitation of the coal deposit in the area whereas the eastern and northern faces of the incline 1-2 are filled with water. Similarly in incline No. 5-7 the south western as well as southern faces of the coal mine can be taken up for the exploitation of the coal deposit on dewatering of the faces of mine by using heavy duty pumps since, the mine have potential of good quality coal seams of the lower coal measures (LCM).

j) Beryal Coal Mine:

Beryal coal mine was established in the year 1998-99 and the record reveals that production was started in the year 2000-01. The lower seam of the upper coal measures was exploited from the Beryal coal mine. Six inclines were driven in the area to exploit the deposit. The coal exploited

was bituminous to semi-anthracitic in nature and dispatches were to the tune of 18,652.315 tons. The mine was closed in the year 2013 due to following reasons (i) High gradient, (ii) High make of water, (iii) Erratic behaviour of the coal seams i.e. all of sudden pinching, (iv) High sulphur content in the coal and (v) Poor roof rocks.

It was observed during the drivages of heading in coal mine there was high make of water. Small capacity pump (10 HP) was installed in the incline for de-watering purposes which could not control the high make of water in the coal mine. The de-watering problem becomes more difficult on steep gradient as in the Beryal coal mine. The said coal mine may be revived to exploit the remaining coal reserves as per the norms and guidelines of mining laid down by the Directorate of Mine Safety and Ministry of Coal Mines, Govt of India, since, only 18,652.315 tons of coal reserves have been exploited so far against total coal reserves of 72, 389 tons reported by the Department of Geology and Mining Jammu.

k) Kotla Coal Mine:

Kotla coal mine was started in the year 2002 and three inclines were driven on the northern limb of the Great Limestone. The coal deposit exploited from the Kotla coal mine was of bituminous to semi-anthracitic in nature. The bed rock over which the mine was established has 1:2 gradient and the coal seam exploited was of upper coal measures (UCM). The roof rocks are poor since the area has been affected by the emergence of Great Limestone which is evident by the presence of Breccia at site. The Department of Geology and Mining has conducted exploration in the said area in the year 1977-78 to 1980-81, 1998 and 2006-07. In preliminary stage of exploration total probable coal reserves reported by the Department of Geology and Mining Jammu were to the extent of 63,000 tons. The record of the total dispatches up to 2012 when the mine was closed were to the tune of 10,783.500 tons against the total reported reserves of 63,000 tons. The coal mine has been revived for exploitation of the coal and is operational as on date.

l) Chakkar Coal Mine:

The Chakkar Coal Mine was established in the year 1968-69. The coal of the upper coal measures (UCM) was exploited by open cast method and the total production made was 1, 08, 488 tons. The mine is located at an elevation of 1019 m a m s l having coordinates N 33°09'6.43", E 74°37'26.1" which was closed in the year 1989 due to exhaust of the coal deposit.

m) Jangalali Coal Mine:

In Jangalali area in District Reasi the exploration was taken up by the Department of Geology and Mining in the year 1962-63 with the objective to explore the potential of the coal deposit in the area. 59 Nos. of exploratory borehole were drilled besides a total 13 drive to the extent of

426.94 meters were also driven. The Geological Survey of India has also conducted detailed exploration in the area and 06 numbers of exploratory boreholes were also drilled. The coal seams present in the area have erratic behaviour and do not have good quality coal beside consistency/thickness in dip as well as in the strike direction. The coal seams of both upper and lower coal measures were encountered. It is pertinent to mention that the coal deposits were exploited by a private firm M/S Kothiyala, the production record of which is not available in the department.

Sapphire (Padder) Mine:

The Mining Lease of Sapphire was granted to M/S. JK Minerals Ltd, a Corporation of the Government of Jammu and Kashmir for exploitation of such valuable gem stone. Accordingly JKML established underground mines and worked so many years in the area. The Lease was withdrawn by the Government with the aim to explore the area through Mineral Exploration Corporation Ltd. (MECL) a premier Corporation of Govt. of India. During the year 2023-24 MECL was assigned the job to conduct investigation to explore the sapphire in the area to develop new mines for the exploitation of the world famous Sapphire. The investigation so conducted will definitely be helpful for establishment/upgradation of the already existing old underground sapphire mines so that the world famous valuable Gemstone shall be exploited with Scientific approach with usage of advance and latest equipments for development of underground mines which was done earlier with old traditional methods.

River Bed Mining:

The Minor Mineral Blocks of River Bed Mining (RBM) have also been e-auctioned after the Amendment of the Minor Mineral Concession Rules issued vide SRO 105 dated 31-03-2026 and NGT Guide lines of 2016 and 2020. Accordingly 225 Minor Mineral Blocks were e-auctioned by the Department and out of which 207 Mining Leases were granted 137 in Jammu Division and 70 in Kashmir Division besides 31 numbers of Quarry Licenses have also been granted out of which 17 quarries are operational as on date. The MMB where mining leases are operational the mining is done as per the standard procedure laid down in the Sand Mining Guidelines 2016 & 2020. The rivers under mining where blocks are carved out are unable to meet up the huge demand of the construction material due to various developmental activities of the projects, keeping in view the Department has planned to locate quarry sites an alternate source of River Bed Mining.

Grant of Quarry Licenses:

As on date the department has focused to identify Quarry sites (In-situ Deposits) of minor minerals to be leased out for accord of mining lease/quarry license for the period applicable under rules. With the adoption of this methodology the river where MMBs were leased out can

be saved from downsizing and degradation of the area besides the extra load on such rivers would be eased out to restore the glory of the rivers and adjoining areas. The mining whether of Major or Minor Minerals is one of the important sector contributing in the GDP and economy of our country and providing direct or indirect employment opportunities to unemployed youths.

The present scenario of the Indian Mining:

Economic Importance: The mining sector contributes about 2.5% to India's GDP and creates millions of jobs.

Mineral Production: India produces a wide range of minerals, including coal, iron ore, bauxite, mica and chromite.

Policy Reforms: The Mines and Minerals (Development and Regulation) Amendment Act, 2023, aims to encourage private sector participation and exploration, and auctions are now common for granting mining leases.

Technological Adoption: Smart mining technologies, including AI, IoT, and automation, being implemented to improve efficiency and reduce environmental impacts.

Environmental Concerns: Mining activities often lead to land degradation, pollution, and other environmental issues.

Global Ranking: India ranks among the top global producers of several minerals, including iron ore, aluminum, lime, mica and coal.

Market Size and Growth: The Indian mining market is substantial with projections for continued growth.

Challenges: Challenges include environmental concerns, land acquisition/use disputes/conflicts and the need for technological modernization to improve efficiency and reduce environmental impact.

Strategic Importance: India holds vast mineral reserves, including coal, iron ore, bauxite, and critical minerals like lithium and rare earth elements.

Economic Contribution: The mining sector contributes significantly to India's GDP and employment, providing jobs directly/indirectly to millions.

Social Considerations: Mining can lead to displacement and loss of livelihood for local communities, necessitating comprehensive rehabilitation and community engagement.

Future Scope of Mining:

It is out of place to mention that there is a lot of scope of mining in the Jammu and Kashmir as well as in India. It will definitely play a significant role if mining is being done with care of environment degradation, sustainable and people friendly atmosphere. If mineral wealth is not conserved for future there may be great loss to the country not only in respect of finance but in mineral resources too. It is the right

time that we have to work out other sources of revenue realization by manufacturing sophisticated war Equipments, Machinery, Medicines, other various day to day required instruments which can be exported to other countries.

The Future Perspective of the Indian Mining:

Sustainable and Responsible Mining: The focus will shift towards environmentally sound practices, waste management, and community well-being.

Technological Transformation: Automation, AI, and digitalization will play a key role in optimizing operations, enhancing safety, and improving productivity.

Circular Economy: Recycling and reusing resources will become increasingly important to reduce waste and promote resource efficiency.

Strategic Reforms: Simplifying regulations, promoting transparency, and attracting long-term investments will be crucial for fostering a thriving mining sector.

Global Leadership: India has the potential to become a global leader in mining, particularly in critical minerals, through strategic investments and technological innovation.

Private Sector Participation: Increased private investment and foreign direct investment (FDI) are anticipated due to policy reforms.

Water Management: Innovations in water management, including water reuse and efficient irrigation techniques, are being explored to reduce water consumption.

Technological Innovation: Further advancements in automation, robotics, and AI are expected to improve efficiency and safety in mining operations.

Automation and Robotics: Automation in mining equipment, including trucks, drilling equipment, and excavators, is increasing.

Rehabilitation of Mined Areas: Rehabilitation measures, such as afforestation and land restoration, are being implemented to mitigate environmental damage.

Growth Potential: The Indian mining sector is expected to continue its growth trajectory, driven by increased demand for minerals from various sectors, including infrastructure, energy, and the automotive industry.

Focus on Sustainable Practices: There's a growing emphasis on sustainable mining practices and ESG compliance to address environmental concerns.

Critical Minerals: The demand for critical minerals like lithium, cobalt, nickel, and graphite is expected to rise, driven by the growing electrification of vehicles and energy transition.

Community Engagement: There's a growing emphasis on community engagement and social responsibility to ensure that mining activities benefit local communities and minimize negative impacts.

Conclusion:

On the basis of field observation and perusal of the data available in the Department of Geology and Mining, it has been concluded that the mining sector is contributing in the GDP and economy of our country by providing Revenue to the Government Exchequer, direct/indirect employment opportunities to unemployed youths and raw material for the establishment of mineral based industries. There is a lot of scope of mining in the country which will definitely play a significant role, if mining is being done with care of environment degradation, sustainable and people friendly atmosphere. If mineral wealth is not conserved today, there may be great loss to the country not only in respect of finance but also of mineral resources. It is the right moment to use them judiciously and conserve our mineral wealth besides to work out other alternate sources to be utilized in place of minerals

Acknowledgment :

The author is highly thankful to the Director, Geology and Mining Department J&K for providing me the opportunity to present the paper in the seminar organized by Mining Engineers Association of India in association with Indian Bureau of Mines. Thanks are also due Joint Director, Geology and Mining Department, Jammu for timely support. The author is thankful to Dr. J.S. Pawar, Geologist Geology and Mining Department Jammu for valuable suggestions while completion of the paper. Support provided by my family to conduct work is also acknowledged.



Review of Ore types, Reserves & Resources, Exploration, Production & Processing of Indian Graphite with reference to Global Scenario

Anirban Das^{1*}, Rupendra Singh Rathore¹, Dr Raziullah Khan¹, Nipam Joshi¹, Arjun Deshpande¹

¹ Asst. Mineral Economist (Intelligence), Mineral Economics Division, Indian Bureau of Mines, Nagpur-440001

*Corresponding Author email: anirban.das13@ibm.gov.in

*Corresponding Author Contact No: +91-8100174108

Abstract

The importance of graphite is rapidly increasing with the global shift towards carbon neutrality and clean energy transition. Graphite is classified as one among the top critical minerals keeping in light its high economic importance and high supply risk considering the prevailing geopolitical scenario around the globe. Graphite is basically categorized into two main types: natural graphite and synthetic graphite. Distribution & quantity of Freehold & Leasehold Graphite Deposits in India highlighted the under explored areas with immense potential. Recent exploration results of India indicate the further opportunity to delineate the identified resources in strike and dip direction using suitable geophysical, geochemical and deep drilling technology. Huge amount of remaining resources were reported by exploration agencies in past in Arunachal Pradesh (76.32 Mt), Jammu & Kashmir (62.74 Mt), Jharkhand (17.40 Mt) & Orissa (17.14Mt). Detailed Exploration strategy can convert these identified deposits into future mines and a step towards achieving the goal of becoming Aatmanirbhar Bharat.

Contribution of India in terms of graphite production has improved from 2.0% 7.5% during 2018 to 2023. Unexplored deposits of countries like Madagascar, Tanzania, Sri Lanka are the low hanging fruits in global context. Methodological statistical data analysis, Geological modelling, Gap analysis and detailed exploration planning & execution can lead to major brownfield mineral discovery. However, for Greenfield discovery, comprehensive analysis of the geological strata of these identified regions, utilizing magnetic, self-potential and geochemical methods to identify ore-forming strata will be a game changer.

Introduction

The global transition to clean energy demands swift and decisive action to combat climate change. Renewable energy systems and electric vehicles (EVs) depend on substantial quantities of critical minerals such as lithium, nickel, cobalt, copper, graphite, and rare earth elements (REEs) to produce high-performance batteries, wind

turbines, and other low carbon technologies (IEA, 2024; IRENA, 2024). Among these critical minerals, graphite stands out as the primary anode material in lithium-ion batteries due to its outstanding electrical conductivity, layered carbon structure for effective ion intercalation, and comparatively low cost (Zhang et al., 2021). Structurally, graphite is known to crystallise in hexagonal system and occurs in layered & lamellar form with grey-to-black metallic lustre and a greasy feel. Natural graphite is categorised into two commercial varieties (i) crystalline (flaky) graphite and (ii) amorphous graphite. Both flaky and amorphous varieties of graphite are produced in India. The quality of graphite depends upon its physical qualities and carbon content. Besides natural graphite, there is synthetic or artificial graphite which is manufactured on a large-scale in electric furnaces, using anthracite or petroleum coke as raw feed.

In the current study, we have discussed about the characteristics and distribution of worldwide known graphite deposits. We have also compiled all reserve-resources data from National Mineral Inventory as on 01.04.2020 and carried out review on previous exploration. Distribution, reserves & resources quantity of freehold & leasehold Graphite deposits in India has been plotted on India Map. Using basic GIS tools & geological confidence based on previous exploration data, high potential areas have been demarcated. This can be used to develop future Exploration strategy of Graphite in India & potential exploration/mining licences can be auctioned subsequently. New geo-technologies for the mineral exploration community are constantly emerging & key technologies like 3D geological orebody modelling, structural data modelling, predictive statistical modelling & integration with obtained Hyperspectral information can pull all these developments together under one roof is 3-D GIS. At advance stage, the scale integration of local observations with more regional interpretations can also be used to generate key productive geological target that shapes the exploration strategy of the whole field.

General review of mining & beneficiation of natural graphite ore with future opportunities has been discussed. Reserves and resources, production data and future opportunities of Graphite Exploration, mining and beneficiation has been discussed in Global scenario. It was observed that, unexplored deposits of nearby countries (e.g., Madagascar, Tanzania, Sri Lanka) are the low hanging fruits. Methodological statistical data analysis, geological modelling, gap analysis and detailed exploration planning & execution can lead to major discovery. Subsequently, this may have the potential to contribute significantly to the global supply chain of Graphite production.

Characteristics & distribution of graphite worldwide:

Carbon exists in various forms across the Earth's crust, atmosphere, oceans, and organic matter. In the Earth's crust, 80–90% of carbon is found as carbonate minerals, while graphite accounts for only about 0.5% of crustal carbon. Graphite can be categorized into two main types: natural graphite and synthetic graphite. Most natural graphite forms through high-temperature thermal metamorphism of organic matter found in sedimentary rocks or subsurface organic deposits. In modern times, synthetic graphite is also widely produced. Battery-grade graphite includes natural graphite and synthetic graphite, each with unique characteristics. Major characteristics of graphite are listed in bellow in Table I (Modified after Fastmarkets, 2024; Robinson et al., 2017; USG, 2024, Park et al., 2025).

Natural graphite is less expensive but has relatively lower charge–discharge efficiency and a theoretical capacity. Synthetic graphite, on the other hand, is more purified, better suited for fast charging/discharging, but has a slightly lower theoretical capacity (Zhao et al., 2022). Due to these complementary properties, secondary batteries for vehicles often use a mix of both.

Amorphous (also called microcrystalline or cryptocrystalline) graphite deposits are generated through the metamorphism of coal, petroleum reservoirs, or other

high-carbon sedimentary rocks. Major global deposits of amorphous graphite are located in Sonora, Mexico; Siberia, Russia; Austria and Ukraine in Europe; and the coal-rich regions stretching from China to the Korean Peninsula (Taylor, 2006).

However, flaky (or crystalline) graphite deposits are predominantly found in metamorphic rocks such as schist, gneiss, quartzite and marble. These deposits form when carbonaceous material in host rocks transforms into graphite during regional metamorphism. Typically, this occurs under amphibolite facies metamorphic conditions, leading to the crystallization of well-aligned order and recrystallization of the rock matrix (Landis, 1971). Notable flake graphite deposits are found in Brazil, Canada, China, and East Asia. In particular, the Jixi district in Heilongjiang Province, China, and Madagascar are known for their world-class, high-quality flake graphite resources (USGS, 2024).

Vein (or lump) graphite has a crystalline structure and forms as veins in high-temperature regional metamorphic environments. These deposits are associated with igneous intrusions into metasedimentary belts (Robinson et al., 2017). Sri Lanka hosts the most economically significant vein graphite deposits. In these deposits, carbon is transported by metamorphic fluids through oxidation/reduction reactions, cooling, or mixing processes, leading to the formation of high-purity graphite veins (Touret et al., 2019).

Synthetic graphite is manufactured from petroleum by-products like needle coke and pitch through a high-temperature graphitization process at approximately 3000 °C. This process produces highly purified and refined graphite, making synthetic graphite more widely used than natural graphite in many applications (Lee et al., 2015).

Natural graphite is less expensive but has relatively lower charge–discharge efficiency. Synthetic graphite, on the other hand, is more purified, better suited for fast charging / discharging, but has a slightly lower theoretical capacity.

Graphite type	Natural graphite			Synthetic
	Amorphous	Flake	Vein	
Appearance				
Crystallinity	Microcrystalline	Crystalline	Crystalline	Microcrystalline to crystalline
Origin	Contact metamorphism, often by diabasic or granitic intrusions, and (or) regional metamorphism of carbonaceous sediments, often coal	Regional metamorphism of carbonaceous sediments at or exceeding amphibolite facies conditions	Epigenetic veins and lodes formed from metamorphic fluids in high-grade metamorphic rocks, usually granulites	Produced by heat treatment (graphitization) of, or chemical deposition from, hydrocarbon materials above 3000 °C
Orebody	Layers, seams, and lenses in carbonaceous rock; may be folded and faulted	Strata-bound; tabular or lens form. Irregular in hinge areas of folds	Vein and fracture-filling within or crosscutting metamorphic structures and rock contacts	NA
Ore Grade (%Total Graphite)	25–60 (locally higher than 90)	5–30 (locally higher than 60)	40–90	NA
Concentrate Grade (%TGC)	60–90	75–95 (95% for battery)	90–99.9	99.95
Major producers	China, Mexico, India	China, Madagascar, Mozambique, Canada, Australia, India	Sri Lanka	China, Japan, South Korea
Main uses	Refractories, steel industry, paint	Battery, Refractories, brake linings, lubricants, expendable graphite	Carbon brushes, brake linings, and lubricants	Batteries, carbon brushes, graphite electrodes, nuclear moderator rods

Table I: Characteristics of graphite by classifications (Modified after Fastmarkets, 2024; Robinson et al., 2017; USG, 2024, Park et al., 2025)

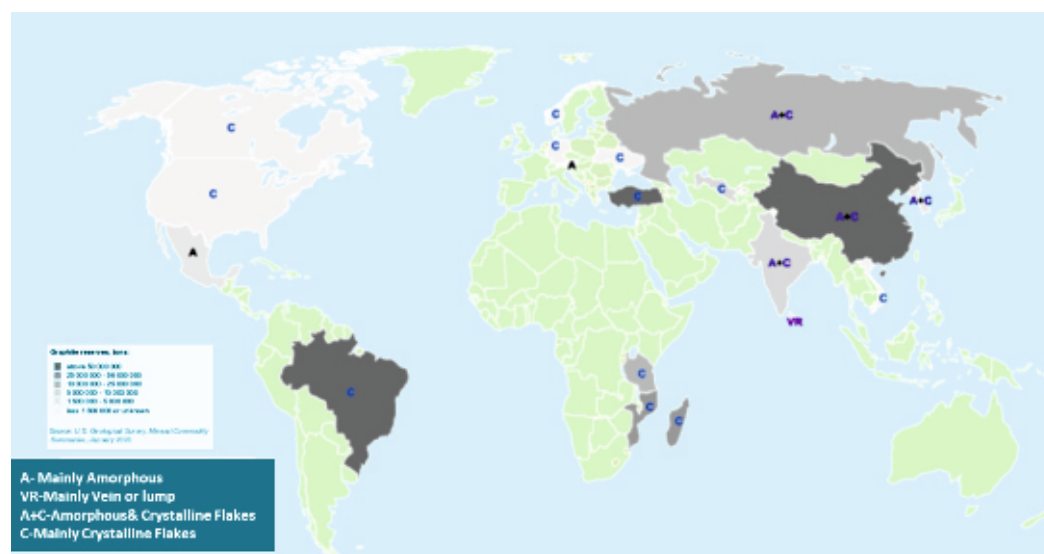


Figure 1: Worldwide distribution of different types of Natural Graphite deposits.

Exploration Potential of Graphite in India:

Exploration of natural graphite primarily leverages its distinct electrical properties, particularly its relatively high electrical conductivity compared to other minerals. The techniques such as electromagnetic (EM), self-potential (SP) and induced polarization (IP) surveys are widely recognized for their effectiveness in identifying graphite deposits (Dentith & Barrett, 2003; Riva et al., 2019). In contrast, gravity surveys are less commonly utilized due to graphite's density (2.2-2.6Kg/m³) being comparable to that of surrounding host rocks, making differentiation challenging unless associated with sulphide minerals (Scott, 2014).

Furthermore, graphite deposits rarely occur in massive, homogenous forms; instead, they are often vertically distributed within complexly folded geological structures, further reducing the utility of gravity-based methods. Similarly, magnetic susceptibility surveys are infrequently applied, as graphite's magnetic properties do not remarkably differ from those of the host rocks.

Recently in India, we have witnessed success in terms of Graphite Exploration in G2, G3 & G4 Levels. The details of a few potential Graphite blocks in India (taken from General Exploration review of IMYB 2023) are described in subsequent paragraphs:

G-4 stage of investigation was carried out in Kolhudhana-Selu-Chauki Pangra areas, Madhya Pradesh, Betul for exploration of Graphite, Basemetal and associated mineralisation. The analytical data shows Cu upto 110 ppm, Pb upto 25 ppm, Zn upto 95 ppm in sheared porphyritic granite. Channel sample across graphite body shows FC upto 15.9%, moisture 1.37%, volatile matter upto 7.71%, ash content 81.26%, vanadium 1548ppm, Thorium 8.60 ppm, Uranium 5.95 ppm. 5.95 ppm.

G-3 stage of investigation was carried out in Bahera-Goriara

block, Madhya Pradesh for exploration of graphite, basemetal and REE mineralisation. 776.2m of exploratory drilling were carried out in 10 drill holes. With the help of cross section method; a cumulative tonnage for copper rich lodes was calculated to 1118831.27 tones, 0.57% average grade, and 9.15 m average thickness and that of graphitic rich lodes was calculated to 1223537.80 tones, 5.16% average grade, and 7.54 m average thickness. With the help of longitudinal vertical section method, a cumulative tonnage for copper rich lodes was calculated to 1105596 tones, 0.58% average grade, and 9.13 m average thickness and that of graphitic rich lodes was calculated to 1218258.12 tones, 5.16% average grade, and 7.52 m average thickness.

G-2 stage of investigation was carried out in Oranga-Revatipur area, Chhattisgarh for exploration of Graphite. Ore beneficiation studies for bulk drilled core sample of the Oranga-Revatipur area assayed with 4.90% Fixed Carbon (FC), 3.05% Volatile matter, 0.32% moisture and 91.73% Ash content. The grade of the graphite concentrate could be upgraded up to 68% FC, with 66.43% recovery (wt% yield: 4.79%). A total of 7.04 million tonnes indicated resource (332) was estimated by cross section method and 6.67 million tonnes by L-V panel method with average grade of 5.47% of fixed carbon at 2% cut off grade. This block has been auctioned and taken by Coal India Limited at a whopping premium of 189.75%.

G-2 stage of investigation was carried out for exploration of Graphite and Vanadium. Drilling at G3 stage estimated a graphite resource of 12.61 MT at a 2% cut-off grade and 10.31 MT at a 5% cut-off grade. Vanadium was also associated with graphite mineralisation. Adhmaniya block, Jharkhand was further explored in the G2 stage, involving the drilling of 19 boreholes. Significant graphite mineralisation was encountered, with varying grades in different boreholes. Vanadium was also identified, showing a positive correlation with graphite content.

G-3 stage of investigation was carried out for exploration of Graphite in Nayagarh, Odisha. A total 2089m of drilling were done in 38 boreholes. Based on the analytical results, in the borehole no. ODT-6 (Band-I), average FC of 2.98% is analysed in 25.5 m thick graphite zone (28 m to 53.5 m). In borehole no. ODT-22 (Band-III), average FC of 4.45% is analysed in 29.5 m thick graphite zone (24.5 m to 54 m).

These exploration results indicate the further opportunity to delineate the identified resources in strike and dip direction using suitable geophysical, geochemical and deep drilling technology.

Reserves & resources of Indian Graphite:

Graphite occurrences are reported from various States but the deposits of economic importance are located in Chhattisgarh, Jharkhand, Odisha and Tamil Nadu.

As per NMI database, based on the UNFC system, the total reserves/resources of graphite as on 1.4.2020 have been placed at about 211.62 million tonnes, out of which 8.56 million tonnes are in the Reserves category and 203.6 million tonnes are placed under Remaining Resources category. Resources containing +40% fixed carbon constitute about 2.91 million tonnes and resources analysing 10–40% fixed carbon constitute 43.98 million tonnes.

The balance 164.72 million tonnes fall under Beneficiable 'Others', 'Unclassified' and 'Not-known' grades. Arunachal

Pradesh accounts for 36% of the total resources which is followed by Jammu & Kashmir (29%), Jharkhand (9%), Madhya Pradesh (5%), Odisha (9%), and Tamil Nadu (4%). However, in terms of reserves, Tamil Nadu has the leading share of about 36% followed by Jharkhand (30%) and Odisha (33%) of the total reserves.

Almost 163.93 Mt resources are not having any grade information. Hence a detailed review of previous exploration to be made and accordingly future exploration strategy to be decided for upgrading the mineral resources to reserves.

Huge amount of remaining resources were reported by exploration agencies in past in Arunachal Pradesh (76.32 Mt as per NMI 01.04.2020) & Jammu & Kashmir (62.74 Mt as per NMI 01.04.2020). From global literature on graphite research, it has been observed that some of the high-grade graphite deposits, faces significant exploration challenges owing to dense vegetation and limited bedrock exposure. Comprehensive analysis of the geological strata of these identified regions, utilizing magnetic exploration, self-potential methods to identify ore-forming strata. However, comprehensive geo-statistical analysis, geological 3D modelling of the ore bearing horizon using the of depth information (e.g., drilling data, trench data) in the region will also guide to develop further exploration strategy and identify the mineral potential blocks for economic extraction.

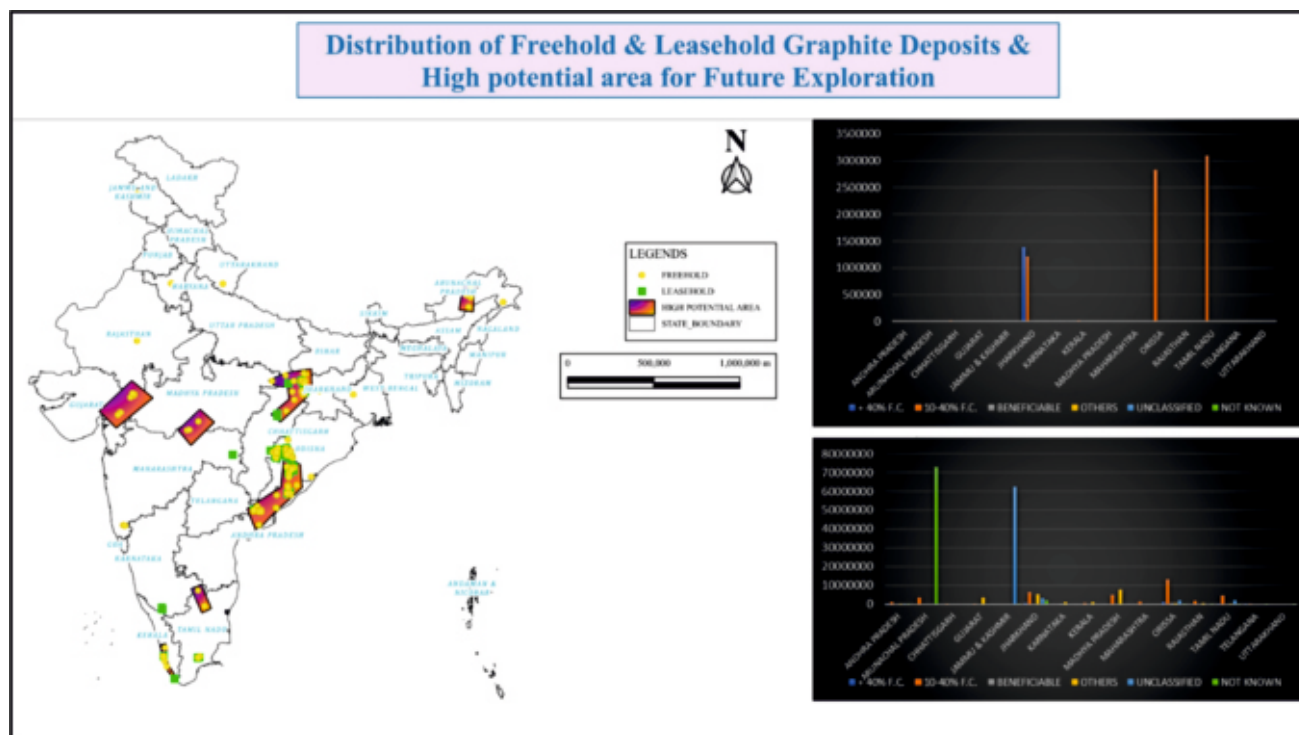


Figure 2: Distribution & quantity of Freehold & Leasehold Graphite Deposits in India. High potential area for future Exploration has been marked in India Map.

Mining & beneficiation of Natural Graphite:

Graphite deposits are mined using conventional mining methods. Flake graphite deposits are typically found near the surface and, depending on the degree of weathering, can be mined using conventional hard or soft-rock mining techniques. Amorphous graphite deposits are exploited using conventional coal-type extraction techniques, while vein graphite deposits can be mined using open pit or conventional shaft methods. While flake and amorphous graphite deposits are currently mined in both underground and open pit operations, vein graphite deposits are almost exclusively mined in underground operations.

In India, active mining centres of graphite are in Palamu district in Jharkhand; Nawapara & Balangir districts in Odisha; and Madurai & Sivagangai districts in Tamil Nadu. Disseminated deposits of flaky graphite containing 5 to 20% Fixed Carbon (F.C.) are found in Palamu district of Jharkhand (for map locations see Figure 2). In Odisha, areas in and around Balangir are the chief mining centres where several graphite grades are produced. At Balangir, a few opencast workings are deeper than 45 m from surface and the R.O.M. from such mines generally contains 10 to 20% F.C. Sargipalli underground mine in Sambalpur district, operated by M/s T.P. Mineral Industries (TPMI), produced graphite that analysed up to 40% F.C. in the past. Water seepage beyond 6 m depth is the main problem faced by almost all mine owners in Odisha.

Mining is considered to be easy and safe as regards graphite deposits in view of their comparatively soft nature and presence of hard rocks on either side. In order to expose graphite deposit, thickness of 1 to 2 meters of top lateritic soil is dozed out using dozer or removed by excavator and loaded through dumper and transported to separate dump yard located in non-mineralised zone in the lease area. The graphite ore obtained usually is transported to stock yard for blending. In stock yard, both high-grade and low-grade ores are stacked separately. Depending on plant requirements, blending work is carried out and blended ore is despatched for consumption. Tamil Nadu Minerals Ltd (TAMIN) has over 600 acres of graphite-bearing areas in Pudupatti, Kumaripatti and Senthudayanathapuram of Sivagangai district, Tamil Nadu (for map locations see Figure 2).

Beneficiation techniques depend on the type of ore, flake size distribution, and the required specifications of the final concentrate such as crystallinity, texture of the flakes, ash content and level of impurities. They can be divided into comminution, beneficiation and for flake graphite, refining stages. Comminution process focuses on the liberation of graphite flakes from the host rock to increase the recovery during the different beneficiation stages. The liberation of graphite flakes is critical for the ultimate grade of the final product.

However, as flake size and carbon content are important commercial considerations. A simplified natural graphite beneficiation flowsheet is shown in Figure 3 below. A combination of crushing and grinding techniques using ball mills, hammer mills, air jet mills and rod mills may be

employed, with a number of screening stages to maximise recovery of large flakes. Attrition scrubbing processes to remove impurities while preserving crystallinity of the graphite flake may follow milling and grinding.

The common processes adopted are washing, sorting, tabling, and acid leaching and froth flotation. Amongst these, froth flotation process is used widely as it helps in producing a fairly high-grade graphite concentrate. Sometimes, beneficiated concentrate is further enriched by chemical treatment (acid leaching, chlorination, etc.) to obtain a very high-grade concentrate containing 98 to 99% F.C.

Prominent beneficiation plants for graphite in India are Chota Nagpur Graphite Industries and Carbon & Graphite Products, Daltonganj; Agrawal Graphite Industries, Gandhamardhan Graphite Udyog and T. P. Minerals Private Limited, Sambalpur; Tamil Nadu Minerals Ltd (TAMIN), Sivagangai, etc.

The ROM, containing an average of about 10% F.C. has to be invariably beneficiated before marketing. Indigenously fabricated equipment is used generally to upgrade the ROM to produce marketable grade graphite which contains normally 70 to 80% F.C. About 92% F.C. product has been obtained by many producers after repeated cycles of beneficiation. A few plant owners have claimed to have obtained product containing as high as 95% F.C.

Beneficiation plants in Odisha seem to have been designed for treating +10% F.C. graphite (ROM). In practice, it is seen that lower grade graphite having +5% F.C. is blended with higher grades to meet the requirements of beneficiation plant, i.e., +10% F.C. Thus, low-grade ore analysing +5% F.C. also gets used.

Tamil Nadu Minerals Ltd (TAMIN) produces flaky graphite from a mine in Sivagangai district in Tamil Nadu. The beneficiation plant located adjacent to the mine site is designed to produce 8,400 tpy of natural graphite concentrate containing 96% F.C. with 92% recovery from ROM.

In review of Graphite mineral resources of India, it has been observed that huge low grade (2%-5% FC) resources are there to be explored & mined with application of suitable beneficiation technology.

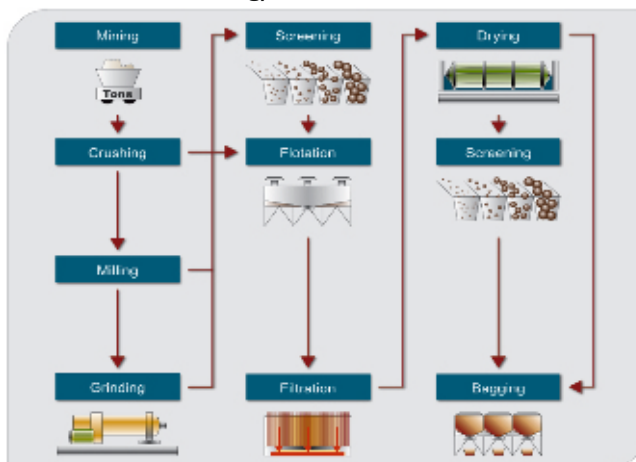


Figure 4: Simplified beneficiation flowsheet for natural graphite.

Bench-scale beneficiation studies were carried out on lean grade Graphite ores of G2 stage exploration samples (IMYB 2023). Amenability to beneficiation of the graphite ores was assessed and suitable process routes were developed.

The graphite ore from Nabarangapur district, Odisha, assayed 2.28 % Fixed Carbon, 94.83% ash, 2.89% volatile matter & moisture. The ash contained 76.18% SiO₂, 9.37% Al₂O₃, 3.94% Fe₂O₃, 1.68% CaO and 2.38% MgO. R&D study employing Froth Flotation technique yielded a composite Concentrate which assayed 58.46% F.C. with recovery of 50.8% F.C. and Wt. % yield 2.0.

The graphite ore from East Godavari district, Andhra Pradesh, assayed 4.54% F.C., 4.76% volatile matter & Moisture and 90.75% Ash. The ash contained 71.26% SiO₂, 5.25% Al₂O₃ and 3.40% Fe₂O₃. R&D studies employing flotation techniques were carried out with primary circuit and secondary circuit (coarse and fine circuits). The combined concentrate assayed 90.02% F.C. with recovery 87.1% F.C. and Wt. % yield 4.4. The concentrate obtained assayed high grade with higher recovery. Also, the study deciphered presence of critical minerals in the tails.

RESERVES & PRODUCTION OF GRAPHITE WORLDWIDE:

The primary producers of flake graphite, which is used in batteries, are China, Brazil, Mozambique, Madagascar & India. The world resources of graphite are believed to exceed 800 million tonnes of recoverable graphite. However, world reserves of graphite have been placed at 290 million tonnes of which China accounts for 27.9% followed by Brazil (25.5%), Madagascar (9.3%), Mozambique (8.6%), Tanzania (6.2%), Russia (4.8%), Vietnam (3.3%), India (3.0%), Korea (1.3%), Mexico (1.1%), Norway (0.2%) & others (3.8%) (Figure 4). Additionally, new mining projects are underway in countries like Tanzania, Canada, and Australia, which are expected to expand graphite production in the near future.

As per publication of British Geological Survey, world production of graphite was 1.72 million tonnes in 2023 as compared to 1.80 million tonnes in 2022. China is the leading graphite producer till 2023, with a share of about 71.4% which is followed by India (7.49%), Mozambique (5.81%), Brazil (3.85%) and Madagascar (3.48%). However, it has been observed that Graphite production has increased significantly from 2020 to 2023, where overall contribution of production has increased from 2.16% to 7.49% (See Figure 5 (A) for distribution of production in world map & Figure 5 (B) & 5 (C) for the chart showing the production quantity of different countries from 2018 to 2023).

In global scenario, contribution of India in terms of graphite production has improved from 31991 MT (2.00% of world production) to 128949 MT (7.49% of world production) during 2018 to 2023

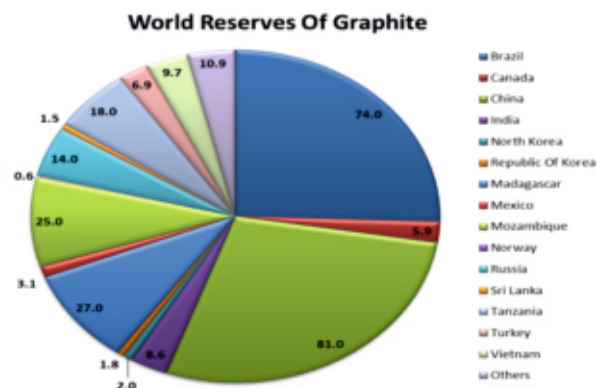


Figure 4: World Reserves distribution of Graphite (Source data from USGS 2024).

China holds a dominant position in the graphite market, both in natural and synthetic graphite, as well as in mining and refining. For example, China Minmetals operates the Yunshan graphite mine, one of the world's largest graphite mines, in Heilongjiang Province. It produces 200,000 MT of graphite annually.

However, the growth in Madagascar's graphite mining industry is being aided by developing projects. For example, NextSource Materials (Molo Graphite Mine) started their commercial production of its SuperFlake graphite concentrate in June 2023. The company is now focused on ramping up plant throughput to its nameplate capacity of 17,000 MT per annum. In October 2024, the company made its first commercial shipments of SuperFlake concentrate from the Molo mine to the United States and Germany.

Brazil has the second highest graphite reserves by country; coming in at 74 million tonnes. Little information is available about the Brazilian graphite-mining industry, as the country's top producers of the metal are private. However, the nation has become a hot spot for graphite exploration and development.

India has several main graphite miners, including Tirupati Carbons & Chemicals, Chotanagpur Graphite Industries and Carbon & Graphite Products. The East African country (Tanzania) is also in the world's fifth largest graphite reserves at 18 million MT.

Sri Lanka hosts the most economically significant vein graphite deposits. The graphite veins in Sri Lanka are unique because of the large scale of their occurrence and their high crystallinity. Similar graphite veins are found in high-grade metamorphic terranes of southern India (Luque et al., 2014) but at a smaller scale though. It was observed that, unexplored deposits of nearby countries (e.g., Madagascar, Tanzania, Sri Lanka) are the low hanging fruits. Methodological statistical data analysis,

Geological modelling, Gap analysis and detailed exploration planning & execution can lead to major discovery. This may also contribute significantly to the global supply chain of Graphite production.

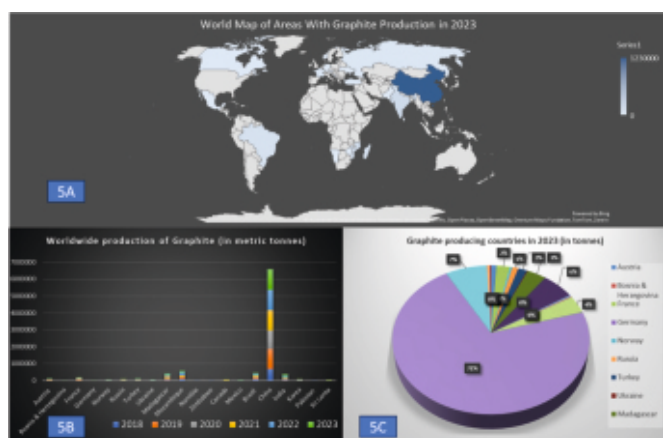


Figure 5: (5A) Showing areas of Graphite Production worldwide. (5B) Showing Bar Chart of global production from 2018 to 2023. (5C) Showing the Pie Chart of Global production of 2023 (Source data from World Mineral Production from 2019-2023, British Geological Survey).

Conclusion:

Worldwide demand for combined natural and synthetic graphite is expected to rise along with improvements in the global economic conditions. Demand is also expected to expand further with the development of non-carbon energy applications, such as; batteries used in electric vehicles, electric devices and energy storage devices that use graphite. In global scenario, contribution of India in terms of graphite production has improved from 31991 MT (2.00% of world production) to 128949 MT (7.49% of world production) during 2018 to 2023. The demand for graphite in the Battery segment is forecasted to at least double in the next few years. A diversified strategy including advanced exploration, cost-effective mining technologies, and standardized trade codes can enhance both sustainability and resilience in the graphite sector in India.

The graphite reserves having +40% Fixed Carbon are rather limited in the country. Detailed exploration of graphite deposits in Odisha, Jharkhand, Arunachal Pradesh, Jammu & Kashmir and Kerala should be carried out. Use of effective geological and geophysical interpretation/re-interpretation will also be a key contributing factor in sustainable development of Graphite resources. Development of multi-dimensional Exploration projects in the identified potential areas may make significant impact on enhancing and upgrading the mineral resources from near-mine to Greenfield mineral exploration activities. In this process a few low-grade deposits may also be identified. Therefore, study on cost-effective beneficiation technologies for low-grade graphite will open up further scope towards using low-grade graphite ore and produce concentrates. Unexplored deposits of countries like Madagascar, Tanzania, Sri Lanka are the low hanging fruits in terms of mining. Graphite is mentioned in Part D of the First Schedule to the MMDR Act for critical & strategic minerals which is essential for our country's economic development and national security.

Acknowledgements:

The authors would like to thank Shri Peeyush Narayan Sharma, Chief Controller of Mines & Controller General (I/c), Shri Pankaj Kulshrestha, Chief Controller of Mines (MES) & Shri P.K. Bhattacharjee, Controller of Mines (MTS), IBM, Nagpur for the constant support and encouragement provided during the study. The constant guidance and support received from Shri D S Walde, Chief Mineral Economist & Shri S.K. Adhikari, Chief Mining Geologist, IBM is thankfully acknowledged. Authors are also thankful to Shri Anirban Paul, Mineral Economist (Int.) & Shri A D Selokar, Mineral Economist (Int.), IBM Nagpur for support extended during technical discussions on previous database of National Mineral Inventory of Graphite.

References:

- Fastmarkets (2024) Graphite market report—10-year forecast (2024.Q3). Fastmarkets Global Limited. p 120.
- INDIAN MINERALS YEARBOOK (2023), Government of India, Ministry of Mines, Indian Bureau of Mines, ISSN 0972-3625
- IEA. (2024). Global critical minerals outlook 2024 (p. 282). International Energy Agency.
- IRENA (2024). Critical materials—Batteries for electric vehicles: International Renewable Energy Agency, Abu Dhabi, 75 p.
- Junhyeok Park., Seong-Jun Cho., Seungwook Shin., Rina Kim., Dongbok Shin., Youngjae Shin. (2025). Overview of graphite supply chain and its challenges. Geosciences Journal, Volume 29, pages 329–341, (2025).
- Landis, C. A. (1971). Graphitization of dispersed carbonaceous material in metamorphic rocks. Contributions to Mineralogy and Petrology, 30, 34–45.
- Robinson, G.R., Hammarstrom, J.M., Olson, D.W. (2017) Graphite: U.S. Geological Survey Professional Paper 1802-J. 1: 24.
- Scott, W.J. (2014) Geophysics for mineral exploration—A manual for prospectors. Newfoundland and Labrador Department of Natural Resources, Canada, p 40.
- Taylor, H.A. (2006) Graphite: Industrial minerals and rocks (7th ed.): Society for Mining, Metallurgy, and Exploration (SME), Colorado, USA. p 1548.
- Touret, J. L., Huizenga, J. M., Kehelpannala, K. W., & Piccoli, F.(2019). Vein-type graphite deposits in Sri Lanka—The ultimate fate of granulite fluids. Chemical Geology, 508, 167–181. <https://doi.org/10.1016/j.chemgeo.2018.03.001>
- USGS (2024). Mineral commodity summaries 2024: U.S. Geological Survey. p 212. <https://doi.org/10.3133/mcs2024>.
- Zhang, H., Yang, Y., Ren, D., Wang, L., & He, X. (2021). Graphite as anode materials—Fundamental mechanism, recent progress, and advances. Energy Storage Materials, 36, 147–170. <https://doi.org/10.1016/j.ensm.2020.12.027>
- Zhao, L., Ding, B., Qin, X. Y., Wang, Z., Lv, W., He, Y. B., & Kang, F. (2022). Revisiting the roles of natural graphite in ongoing lithium-ion batteries. Advanced Materials, 34(18), 2106704. <https://doi.org/10.1002/adma.202106704>.

Graphite: An overview on global demand, supply chain & geopolitics with Indian perspective

Rupendra Singh Rathore-1*, Anirban Das-1, Nipam Joshi-1 & Anirban Paul-2

1 Assistant Mineral Economist (Intelligence), Mineral Economics Division, Indian Bureau of Mines, Nagpur-440001

2 Mineral Economist (Intelligence), Mineral Economics Division, Indian Bureau of Mines, Nagpur-440001

*Corresponding Author email: rupendra.rathore@ibm.gov.in

*Corresponding Author Contact No: +91-7742231537

Abstract

Graphite is one of the modern-era mineral which may bring significant transition in clean energy and steel sectors at a global scale. It is the single largest material by weight in an EV battery-much more than lithium or cobalt. As the world shifts towards clean energy and more EVs hit the road, the demand for graphite is increasing very fast. Global agencies like Bloomberg and the International Energy Agency (IEA) predict that graphite demand could grow 4 to 25 times by 2040. Graphite is of two types: Natural, which is mined from the earth and other one, is Synthetic, made from petroleum by-products. Natural graphite has a lower environmental impact. For use in EV batteries, graphite has to go through several steps like shaping, purifying and coating to become battery-grade. At present, most of the world's battery-grade graphite is refined in China, making it a powerful player in this supply chain. In 2023, China imposed restrictions on certain graphite exports, affecting global supply and prices. This showed how dependent other countries are on China for this important mineral. India, even though it has large reserves and resources of graphite (over 211 million tonnes), still depends on imports. In 2023, India produced about 1.29 lakh tonnes of graphite but still imported around 55,000 tonnes, mainly from Madagascar, China and Mozambique. India ranks second in global production but lacks advanced processing technology. To fix this, the Indian government is taking steps like auctioning new mining blocks, launching the National Critical Mineral Mission (NCMM) and promoting domestic processing through schemes like Production Linked Incentive (PLI). In the future, demand for graphite is expected to rise sharply, not just for EVs but also for mobile phones, laptops, solar energy and other modern needs and uses. India needs to explore its resources better, invest in new technology and build international partnerships to become self-reliant in this key mineral.

Introduction

Graphite is the ideal choice for battery anode material, which is responsible for storing and releasing electrons

during the charging and discharging process. Due to its natural strength and stiffness, graphite is an excellent conductor of heat and electricity, meeting the voltage requirements of not only EV batteries but stationary ones as well.

Today, graphite represents the largest component in EV batteries by weight, constituting 45% or more of the cell. Nearly four times more graphite feedstock is consumed in each battery cell than lithium and nine times more than cobalt.

Needless to say, graphite is very much indispensable to the EV supply chain. Bloomberg NEF expects graphite demand to quadruple by 2030 on the back of an EV battery boom transforming the transportation sector.

The International Energy Agency (IEA) goes 10 years further out, predicting that growth in graphite demand could see an 8- to 25-fold increase between 2020-2040, trailing only lithium in terms of demand growth upside.

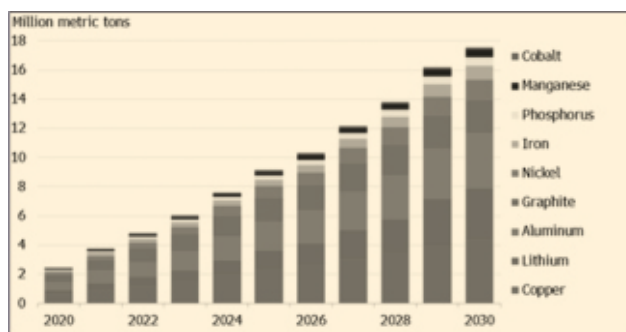


Figure 1: Metals demand from Lithium-ion batteries is expected to top 17 Million tons in 2030 (Source: Bloomberg NEF. Note: Metals demand occurs at the mine mouth, one year before battery demand).

Now the question becomes whether we have enough graphite to sustain the demand pressures of the global EV revolution. To answer that, we first need to understand where the anode material comes from, and what makes graphite so in-demand.

Graphite — A Closer Look

Graphite is a mineral composed of stacked sheets of carbon atoms with a hexagonal crystal structure. It occurs naturally in metamorphic and igneous rocks, where high temperatures and pressures compress carbon into graphite. It's the most stable form of pure carbon under standard conditions.

Graphite is very soft, has a low specific gravity, is relatively non-reactive, and, as mentioned, has high electrical and thermal conductivity. As such, it is used in a wide range of industrial applications including in batteries, pencils, semiconductor substrates, lubricants and synthetic diamonds.

While it comes in many different grades and forms, the graphite used in EV batteries falls into one of two classes: natural or synthetic.

Natural graphite is produced by mining naturally occurring mineral deposits. This method produces only one to two kilograms of CO₂ emissions per kilogram of graphite. Synthetic graphite, on the other hand, is produced by the treatment of petroleum coke and coal tar, producing nearly 5 kg of CO₂ per kilogram of graphite along with other harmful emissions such as sulphur oxide and nitrogen oxide.

To turn either of these into the battery anode material, graphite must go through four overarching steps: mining, shaping, purifying, and coating. Each of these stages results in various forms of graphite with different end-uses.

For instance, the micronized graphite that results from the shaping process can be used in plastic additives. On the other hand, only coated spherical purified graphite (CSPG), which has to go through all four stages, can be used in EV batteries.

It's estimated that an electric car can contain up to 100 kg of CSPG, meaning it could take 10 to 15 times more graphite than lithium to make a Li-ion battery. But due to losses in the manufacturing process, sometimes it can take even 30 times more graphite.

According to the World Bank, graphite now accounts for more than half of the mineral demand in batteries, the most of any. Lithium, despite being a staple across all batteries, accounts for only 4% of demand.

Again, this goes to show how important graphite is to the EV sector, and how much it has been overshadowed by lithium. Graphite is so essential to a lithium battery that Elon Musk famously said: "Our cells should be called nickel-graphite, because primarily the cathode is nickel and the anode side is graphite with silicon oxide."

Supply and demand of graphite:

With the rapid growth in battery demand, the need for graphite is projected to increase substantially due to the current absence of widely available alternatives. By 2030, the demand for battery-grade graphite is anticipated to quadruple compared to 2023 levels, driving an almost two fold rise in total graphite demand over the same period (IEA, 2024).

Graphite is used in a wide range of applications, which makes its supply chain increasingly complex as it moves closer to the final product. As shown in Figure 2, graphite has traditionally been used in refractories, carburizers, and electrodes for electric arc furnaces. However, its use in battery anodes has grown significantly in recent years. Batteries now account for approximately one-third of total graphite demand, with about half of this used in electric vehicle (EV) batteries. Each EV battery requires 50–100 kg of graphite (Olson et al., 2016), and the rapid adoption of EVs is driving a sharp increase in graphite demand.

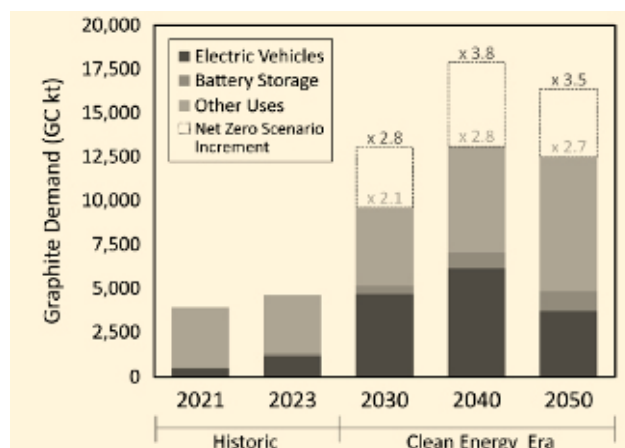


Figure 2: Change in demand of graphite (including natural and synthetic) in clean energy era, based on conservative scenario and net-zero scenario proposed by IEA (2024).

In 2023, according to the U.S. Geological Survey's Mineral Commodity Summaries, the major users of natural graphite included the Batteries, Refractories, Steelmaking, Brake linings, Lubricants, and Powdered metals. USGS data shows that in the United States alone, about 76,000 tonnes of natural graphite were consumed domestically. Although the US does not produce graphite, it imports nearly 84,000 tonnes, of which 89 percent is high-purity flakes. Globally, USGS and allied studies suggest that approximately 80 percent of natural graphite is used in refractory and steelmaking applications, while the battery sector accounts for around 10–15 percent. The remaining share goes to brake linings, lubricants, powder metallurgy, and other industrial uses.

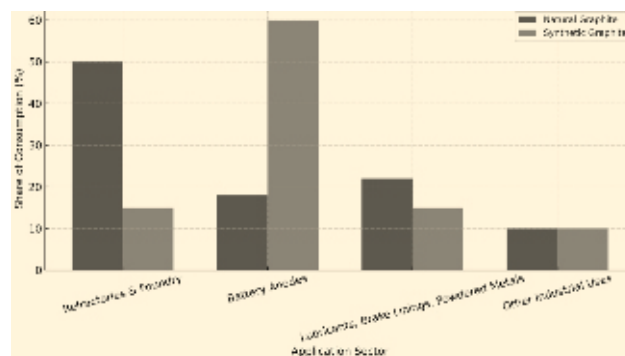


Figure 3: Global consumption of Natural & Synthetic Graphite by Sectors (Source: USGS Mineral commodity summaries 2023; Natural Resources Canada; Research Gate (Graphite Flows, 2023))

Globally, graphite consumption in 2023 reached approximately 5.2 million tonnes, with natural and synthetic graphite each playing distinct roles. According to Natural Resources Canada (which bases its figures on USGS data), natural graphite made up about 1.5 million tonnes, while synthetic graphite accounted for 3.5 million tonnes, representing roughly 67 percent of total graphite use (USGS 2023; NRCan2023).

Breaking this down, around 50 percent of natural graphite is used in refractory and foundry applications, where its high-temperature stability is essential, and 18 percent is used in lithium-ion battery anodes, a proportion that has been growing rapidly (USGS 2023; NRCan2023). Other end uses such as lubricants, brake linings, and powdered metals share the remaining consumption.

In terms of regional demand, Asia dominates usage of both forms, consuming nearly 87 percent of natural graphite and 84 percent of synthetic graphite, with North America and Europe accounting for much smaller shares (USGS 2023; NRCan2023, Fastmarkets 2024).

On the synthetic side, which mainly feeds into battery anodes and electrodes for electric arc furnaces, about 50–70 percent is used for battery applications, while refractories and foundries rely less on synthetic types due to material properties (USGS 2023; NRCan2023, Fastmarkets 2024).

Together, this data demonstrates that although most graphite used today is synthetic, natural graphite remains vital for refractory industries and rapidly growing battery applications. This dual structure underscores graphite's central role in both traditional industrial and emerging clean-energy sectors.

Exports of Graphite:

In 2022-23, exports of graphite (natural) increased by 293% to 2239 tonnes as compared to 764 tonnes in the previous year. Graphite (natural) was exported mainly to Tanzania (25%), Nepal (15%), Malaysia (11%), and UAE (10.1%).

The exports of graphite (artificial) increased by 46% to 29,522 tonnes in 2022-23 from 28,218 tonnes in the previous year. Graphite (artificial) was exported mainly to Germany (14%), U S A (7%), Bhutan (20.5%), UAE (8%), Saudi Arabia (16%), Bangladesh (6%) and Kuwait (5%) (Figure 5).

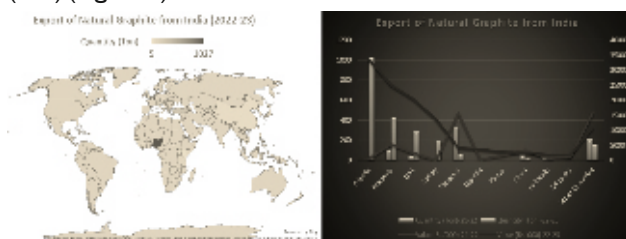


Figure 4: Left side map showing Export of Natural graphite from India to other Countries. Right histogram chart showing comparison of export quantity (Ton) and values (Rs'000) during the FY-21-22 & FY-22-23.

Imports of graphite (natural) decreased by 17% to 45,994 tonnes in 2022-23 from 54,047 tonnes in the preceding year. Graphite (natural) was imported mainly from China (45%), Madagascar (30%), and Mozambique (18%). Imports of graphite (artificial) increased by 9.0% to 82,721 tonnes in 2022-23 from 75,657 tonnes in the previous year. Imports of graphite (artificial) were mainly from China (60%), Germany (12%), Poland (4%) and remaining 24% share was contributed by other countries. Imports of graphite crucibles drastically decreased to nil in 2022-23 from 386 tonnes in the previous year. Imports were mainly from China (97%), Germany (2%) and Netherlands (Figure 6).

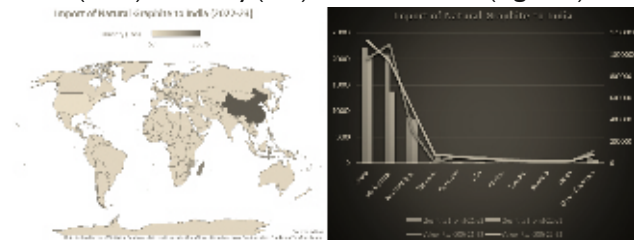


Figure 6: Left side map showing Import of Natural graphite to India from other Countries. Right histogram chart showing comparison of import quantity (Ton) and values (Rs'000) during the FY-21-22 & FY-22-23.

The Geopolitics of Graphite: A Global and Indian Perspective

In era of accelerated technological progress, graphite has emerged out as one of the most significant minerals as it is used in the making of batteries for electric vehicles, in the production of steel, in the storage of renewable energy, and in many other latest & modern technologies. Graphite acts as a very critical anode component in Li-ion batteries; consequently, it happens to be a very significant mineral to bring out green energy transition. Around 90% of the graphite, which is used in battery refining work, is supplied by China, which makes it a dominant and strategic player in regulating the worldwide supply chain of the same (Figure 7).



Figure 7: Schematic maritime trade route from China to India for transporting Graphite consignments.

China restricted the export of some particular grades of graphite in late 2023, adversely affecting the global graphite market and the resulting the price hike of graphite

concentrates. This event brought an alarming situation for most of the nations to look for the alternative options to avoid the supply chain disruption. As a recent instance, Resonac, a Japan-based company, closed down its graphite electrode plants in China and Malaysia because of the challenges encountered in maintaining the constant supply of concerned raw material for the plants. In such a scenario, Indian companies like Graphite India and HEG Ltd., which are dealing in the graphite business, are having the opportunity to perform as a crucial alternative option in order to maintain the constant supply chain. Other nations like the United States and Australia are also making huge investments in order to develop their own graphite supply chain and to avoid dependency on others. As per the media reports, it has come to light that the U.S. government is in talks with a US-based company, Novonix, in order to build a graphite processing plant in the U.S. on a large scale, for which the government itself is ready to provide financial aid.

Scaling the market of graphite at a global scale and considering the latest data published in World Mineral Production 2019-23 by the British Geological Survey, India ranks second in graphite production in 2023, which accounts for around 7.5% of the global contribution. Being a critical mineral in green technology, electric vehicles, and steel production, the demand for graphite is increasing rapidly in the country. As per the latest National Mineral Inventory (NMI) database of India, the total reserves/resources of graphite are about 211.62 million tonnes, mainly concentrated in Arunachal Pradesh, Jammu & Kashmir, Jharkhand, Madhya Pradesh, Odisha, and Tamil Nadu. Although the country has large resources of graphite, it still lacks large-scale processing capabilities. The graphite production in the country landed around 129,000 tonnes in the year 2023; still, it had to import nearly 55,000 tonnes in addition, mainly from Madagascar (45%), China (39%), and Mozambique (10%). This is the perfect indicator, which shows that India is highly dependent on imports of this mineral in spite of having large resources in the country itself.

In order to become self-sufficient in the mineral and mining sector, the Government of India is constantly taking ground-breaking actions. Khanij Bidesh India Limited (KABIL) is also actively looking into the international partnerships with multiple countries to secure and acquire the high-grade graphite assets. The Ministry of Mines has also successfully auctioned around 15 blocks of graphite and the associated minerals up to its 5th Tranche of Critical & Strategic Minerals. Furthermore, the government also introduced the National Critical Minerals Mission (NCMM) and Production Linked Incentive (PLI) schemes to boost critical minerals production in country, consequently supporting India's target to achieve its goal of becoming self-reliant in the mining and the concerned downstream sectors.

In this modern era of advancement and technology, critical minerals have become very crucial for any country's

economic growth & stability and for its national defense & security sector. In light of the same, planning and strategy for securing critical minerals have become a national priority for all. For example, the U.S. is providing financial support to its nation-based companies in order to come up with graphite beneficiation projects domestically. Similarly, India is also coming up with several roadmaps and strategies in order to reduce its import dependency. Considering several factors and the present geopolitical situation round the globe, the International Energy Agency (IEA) also indicated that India is required to expand its graphite resources and must focus on international collaboration with the global south in order to secure its supply chains. Investments in research & development in order to bring out in-house latest technology and processing capabilities are the need of the hour to attain self-resilience in securing the supply chain of critical minerals in a sustainable and eco-friendly manner.

In conclusion, to come up with industry-friendly policies, incentivizing public-private partnerships, financial aid to the domestic players and international cooperation are the keys that have the potential to bring a positive impact on India's aim of becoming self-sufficient in critical minerals, particularly graphite in this context.

Future outlook:

Worldwide demand for combined natural and synthetic graphite is expected to rise along with improvements in the global economic conditions. Demand is also expected to augment further with the development of non-carbon energy applications, such as; batteries used in electric vehicles, electric devices and energy storage devices that use graphite. The graphite resources having +40% Fixed Carbon are rather limited in the country. Detailed exploration of graphite deposits in Odisha, Jharkhand, Jammu & Kashmir and Kerala should be carried out. Cost-effective beneficiation technologies for low-grade graphite ore need to be developed. Silicon carbide-graphite crucibles are being diversified and manufactured to improve upon the use of inferior grade material with less quantity and at the same time ensuring longer life of crucible.

Of late, a few emerging & important specialized applications of exfoliated graphite have been reported especially in the manufacture of sealings, gaskets, braids and brushes. New products of synthetic graphite, such as, graphite fibers/ropes and graphite insulation blankets have been introduced. In the world scenario, there seems to be a rapid diversification in respect of potential large-volume end-use for natural graphite, such as, in heat sinks, also called spreader shield, which is a graphite foil material that conducts heat only in two directions. It has thermal conductivity above aluminium and almost equal to copper. These are used for dissipating heat in laptop computers, flat-panel displays, wireless phones, digital video cameras,

etc. Such emerging & high growth applications of graphite are certainly causing noticeable impacts on the demand & consumption patterns within the country & globally.

The demand for high purity graphite is increasing exponentially due to increase in the demand of lithium-ion batteries for electric vehicles, laptops, smartphones, home/business applications and traditional uses for expanded graphite foils are also the potential areas that are expected to be major drivers for graphite consumption. It represents 23% of global flake graphite demand. The demand for graphite in the Battery segment is forecasted to double in the next six years. Graphite is mentioned in Part D of the First Schedule to the MMDR Act for critical & strategic minerals which is essential for our country's economic development and national security.

Acknowledgments :

The authors would like to thank Shri Peeyush Narayan Sharma, Chief Controller of Mines & Controller General (I/c), Shri Pankaj Kulshrestha, Chief Controller of Mines (MES) & Shri P.K. Bhattacharjee, Controller of Mines (MTS), IBM, Nagpur for the constant support and encouragement provided during the study. The constant guidance and support received from Shri D S Walde, Chief Mineral Economist & Shri S.K. Adhikari, Chief Mining Geologist, IBM is thankfully acknowledged. Authors are also thankful to Dr. S.K. Shami, Superintending Mineral Economist (Int.), Shri Gaurav Sharma, Mineral Economist (Int.), IBM Nagpur for support extended during technical discussions on the subject matter.

References:

Fastmarkets (2024) Graphite market report—10-year forecast (2024.Q3). Fastmarkets Global Limited. p 120.

Graphite Facts—Minerals and Metals Facts Publisher: Government of Canada, Natural Resources Canada (NRCan)

INDIAN MINERALS YEARBOOK (2023), Government of India, Ministry of Mines, Indian Bureau of Mines, ISSN 0972-3625

IEA. (2024). Global critical minerals outlook 2024 (p. 282). International Energy Agency.

Life Cycle Inventory of Graphite Use in EV Batteries, U.S. Department of Energy – Argonne National Laboratory

Mineral Commodity Summaries—Graphite (2023) Publisher: U.S. Department of the Interior, USGS, U.S. Department of the Interior, USGS

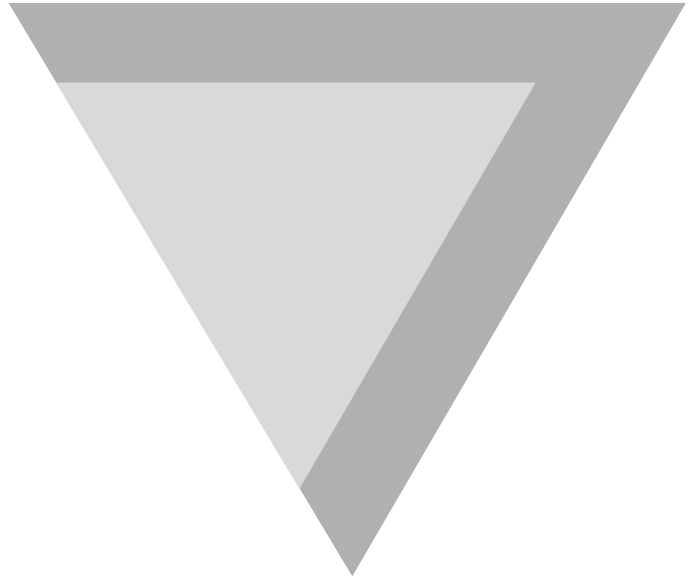
Robinson, G.R., Hammarstrom, J.M., Olson, D.W. (2017) Graphite: U.S. Geological Survey Professional Paper 1802-J. 1: 24.

Taylor, H.A. (2006) Graphite: Industrial minerals and rocks (7th ed.): Society for Mining, Metallurgy, and Exploration (SME), Colorado, USA. p 1548.

USGS (2024). Mineral commodity summaries 2024: U.S. Geological Survey. p 212. <https://doi.org/10.3133/mcs2024>.

Zhang, H., Yang, Y., Ren, D., Wang, L., & He, X. (2021). Graphite as anode materials—Fundamental mechanism, recent progress, and advances. *Energy Storage Materials*, 36, 147–170. <https://doi.org/10.1016/j.ensm.2020.12.027>

Zhao, L., Ding, B., Qin, X. Y., Wang, Z., Lv, W., He, Y. B., & Kang, F. (2022). Revisiting the roles of natural graphite in ongoing lithium-ion batteries. *Advanced Materials*, 34(18), 2106704. <https://doi.org/10.1002/adma.202106704>



Legislative Aspects of Mineral Industry





Major Legal Reforms in India's Mining and Mineral Sector

Rajiv Kumar – Head of Mineral Resources

Pavankumar Kantreddy - Dy. Mines Manager

Sneha Chodankar – Mining Engineer

Fomento Resources Pvt. Ltd

Abstract

India's mining sector has seen major legal and policy reforms over the past two decades to improve transparency, efficiency, and sustainability. The transformation is marked by three key amendments to the Mines and Minerals (Development and Regulation) Act, 1957 in 2015, 2021, and 2023 alongside the National Mineral Policies of 2008 and 2019.

The 2015 amendment introduced auctions as the only mode of mineral allocation, ending discretionary allotments. It also established the District Mineral Foundation (DMF) and National Mineral Exploration Trust (NMET) for welfare and exploration funding. The 2021 amendment further liberalized the sector by allowing captive mines to sell part of their output and ensured the automatic transfer of approvals. The 2023 amendment focused on securing critical minerals like lithium and rare earth elements, opening exploration to the private sector.

Despite auctioning over 500 mineral blocks, only a fraction are in operational, especially in the iron ore sector. This gap is due to delays in clearances, high financial levies, and logistical constraints.

The paper suggests fast-tracking approvals, capping total levies, improving infrastructure, and ensuring timely operationalization of auctioned mines. It highlights the need for better execution to match ambitious legal reforms and unlock India's full mineral potential particularly in supporting the energy transition and strategic industries.

Introduction

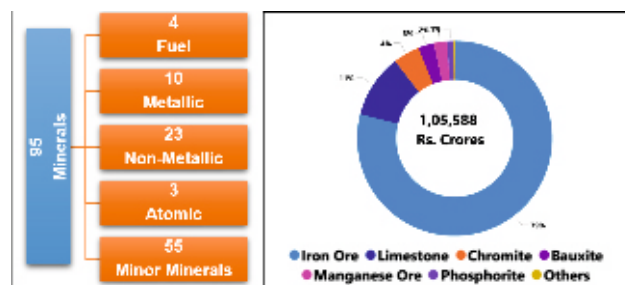
Over the past two decades, India's mining sector has undergone a transformative journey driven by a series of legal and policy reforms aimed at enhancing transparency, sustainability, and economic efficiency. At the core of this transformation lie the significant amendments to the Mines and Minerals (Development and Regulation) Act, 1957 (MMDR Act), particularly the landmark reforms in 2015 and subsequent years.

This paper critically examines these legislative changes especially those impacting the iron ore segment and

evaluates their effectiveness in streamlining mineral block allocation and encouraging sustainable mining practices. The analysis is divided into two broad eras: Kalkhanda I (2005–2015) and Kalkhanda II (2015–2025). We also explore broader policy efforts like the National Mineral Policy and India's growing focus on critical minerals.

The Mineral Overview

Following charts shows the spread of mineral sector along with the value of the mineral in the FY 22-23 in India.



Mineral - wise value of production

The Legal Framework (2005–2015)

Governing Acts and Rules (Pre-2015)

The legal scheme applicable during this period were primarily covered under the Mines and Minerals Development and Regulation Act, 1957, and the Mines Act, 1952. The following table enumerates the majority of the Rules and Regulations applicable to the mineral industry.

Table

Sl.No.	Name	Purpose
1	The Mines Act, 1952 and safety in mines	Regulation of labor
2	The MMDR Act, 1957	Regulation & development of mines and minerals
3	Mineral Concession Rules, 1960	Procedures for mineral concessions
4	Mineral Conservation and Development Rules, 1988	Conservation & systematic development of minerals
5	Auction by Competitive Bidding of Coal Mines Rules, 2012	Rules for coal mine auction

Grant and Renewal of Leases

- i) Initial Grant: Section 8(1) – up to 30 years (with prior approval under Section 5(1)).
- ii) First Renewal: Section 8(2) – up to 20 years.
- iii) Subsequent Renewals: Section 8(3) – permitted only in the interest of mineral development.

National Mineral Policy 2008

The National Mineral Policy, 2008 aimed to promote sustainable, scientific, and transparent mining in India. It encouraged private investment, use of modern technology, and ensured environmental protection and community welfare. The policy emphasized efficient concession granting, infrastructure development, and institutional strengthening. The salient features were:

- i) To ensure that the regional and detailed exploration is carried out systematically in a time bound manner.
- ii) Zero waste mining will be the national goal.
- iii) Transparency in allocation of concessions will be assured.
- iv) Preference may be given to a value addition industry in grant of mineral concession.
- v) The development of a mining tenement registry and a mineral atlas will be given priority.
- vi) Framework of sustainable development will be designed to take care of bio diversity and restoration of the ecological balance.
- vii) Special care will be taken to protect the interest of host and indigenous (tribal) populations.
- viii) Employment and tertiary sector spin-offs from both value addition and mining to be encouraged.
- ix) Mineral bearing States to get a fair share of the value of their minerals.
- x) Institutional framework for Research & Development.

Sectoral Context

- i) 2005–2012 Boom: Rising steel demand from China triggered a massive spike in global iron ore prices and exports. Between 2005 and 2015, Western Australia experienced an iron ore boom, increasing exports from 117 Mt to 500 Mt. India saw similar trends of export of Iron ore which reached to 66 Mt in 2012.
- ii) Royalty Shift (2009): Transition from fixed-rate royalty (/ton) to an ad valorem system.
- iii) Environmental Backlash: Unregulated mining with infrastructure strain led to ecological stress, resulting in court interventions and mining bans in Karnataka, Goa, and Odisha.

MMDR Amendment Act, 2015

To address the serious and ongoing challenges in India's mining sector, the government brought in the Mines and Minerals (Development and Regulation) Amendment Ordinance on 12th January 2015. The purpose of this Ordinance was to bring about urgent reform, and the present Bill was introduced to replace it with a more permanent framework.

- i) To eliminate discretionary powers in granting mining rights.
- ii) To improve transparency in the allocation of mineral resources.
- iii) To make the system more efficient.
- iv) To reduce delays in administration.
- v) To allow quicker and more effective development of minerals
- vi) To ensure a greater share of mineral value reaches the government.
- vii) To encourage private sector investment and adoption of advanced technology in mining.

The relevant portion of the Statement of Objects and Reasons of MMDR, 2015 (Amendment Act 10 of 2015) enumerating the salient features are reproduced hereinbelow :

The salient features of MMDR Amendment Bill, 2015 are as follows:-

- i) Removal of discretion; auction to be sole method of allotment: The amendment seeks to bring in utmost transparency by introducing auction mechanism for the grant of mineral concessions. The tenure of mineral leases has been increased from the existing 30 years to 50 years. There is no provision for renewal of leases.
- ii) Impetus to the mining sector: The mining industry has been aggrieved due to the second and subsequent renewals remaining pending. In fact, this has led to closure of a large number of mines. The Bill addresses this issue also. The Bill provides that mining leases would be deemed to be extended from the date of their last renewal to 31st March, 2030 (in the case of captive mines) and till 31st March, 2020 (for the merchant miners) or till the completion of the renewal already granted, if any, or a period of fifty years from the date of grant of such leave, whichever is later.
- iii) Safeguarding interest of affected persons: There is provision to establish District Mineral Foundation in the districts affected by mining related activities.
- iv) Encouraging exploration and investment: The Bill proposes to set up a National Mineral Exploration Trust created out of contributions from the mining lease

holders, in order to have a dedicated fund for encouraging exploration in the country. Transfer of mineral concessions granted through auction will be permitted in order to encourage private investors.

- v) Simplification of procedures and removal of delay: The amendment removes the need for "previous approval" from the Central Government for grant of mineral concessions in case of important minerals like iron ore, bauxite, manganese etc. thereby making the process quicker and simpler. Similarly, the State Governments will devise a system for filling of a mining plan obviating the need for prior approval of the Mining Plans by the Central Government. The Central Government will have revision powers in case State Governments fail to decide issues within the prescribed time.
- vi) Stronger provisions for checking illegal mining: In order to address the serious problem of illegal mining, the penal provisions have been made further stringent by prescribing higher penalties up to 5 lakh rupees per hectare and imprisonment up to 5 years. State Governments will now be able to set up Special Courts for trial of offenses under the Act."

In order to give effect to these amendments following Rules came to be introduced:

- The Minerals (Evidence of Mineral Contents) Rules, 2015 (MEMCR 2015)
- The Mineral Auction Rules, 2015 (MAR 2015)
- The Minerals (Other than Atomic and Hydro Carbons Energy Minerals) Concession Rules, 2016 (MCR 2016)
- The Minerals (Transfer of Mining Lease Granted Otherwise than through Auction for captive purpose) Rules, 2016. (MTR, 2016)
- The Mineral Conservation and Development Rules, 2017 (MCDR 2017)

The following table shows the amendments along with the cross-references

MMDR 2015

Sr. No.	Objective	Amended/Updated Provisions
1	Lease period	MMDR Act, Section 8-A
2	Process of Grant	MMDR Act Notified Minerals Section 10-B Sub Section (2)- Grant of Composite License • Inadequate Evidence of Mineral (Rule 7 of MEMCR 2015) • Chapter III (Rule 16 to 19 of MAR, 2015) Sub Section (3)- Grant of Mining Lease • Adequate Evidence of Mineral (Rule 5 of MEMCR 2015) • Chapter II (Rule 5 to 15 of MAR 2015) Other than Notified Mineral Section 11 (Rule 4 of The MAR, 2015)

3	Formation of District Mineral Fund safeguarding interest of affected persons	MMDR Act Auctioned leases- presently @10% of Royalty Section 9-B(5) of MMDR Act read with Rule 2(a) of DMF Rules, 2015 Non-Auctioned leases- presently @30% of Royalty Section 9-B(6) of MMDR Act read with Rule 2(b) of DMF Rules, 2015
4	Formation of National Mineral Exploration Trust (NMET)	MMDR Act Section 9-C for formation of NMET a non-profit autonomous body All leases-@2% of Royalty NMET Rules 2015 Governing body Executive body
5	No transfer of mineral concessions	MMDR Act Section 12-A • Transfers allowed only for auctioned leases kindly refer Section 12-A(6) • State Government to decide within 90 days else deemed to have no objection to such transfer Section 12-A(3)

Post the amendment in 2015 which mandated auction of mineral concessions, the Act was further amended in the years 2016 and 2020 to allow transfer of leases for non-auctioned captive mines and to deal with the emergent issue of expiry of leases on 31st March 2020.

National Mineral Policy (NMP) 2019

The goal of the NMP 2019 was to have a mining sector that is efficient, environmentally responsible, and socially inclusive and promotes sustainable, transparent, and efficient mining in India. It focuses on:

- Ease of Doing Business: Simplified clearances, digitization, and transparency in auctions.
- Exploration: Boosting private participation and using modern tech.
- Sustainable Mining: Emphasis on environment, scientific mining, and zero-waste practices.
- Revenue & Investment: Rationalized taxes and better use of DMF & NMET funds.
- Infrastructure & Industry: Stronger transport and value addition.
- Social Responsibility: Welfare of affected communities, especially tribals.
- Skill & Innovation: Support for mining education, training, and R&D.

MMDR Amendment Act, 2021

However, in order to fully harness the potential of the mineral sector, increase employment and investment in the mining sector, increase the revenue to the States, increase

the production and time bound operationalization of mines, maintain continuity in mining operations after change of lessee, increase the pace of exploration and auction of mineral resources and resolve long pending issues that slowed the growth of the sector, it was felt necessary to further amend the said Act. Accordingly, the Act was amended by an Amendment Act 16 of 2021 on 28th March 2021.

The relevant portion of the Statement of Objects and Reasons of MMDR, 2021 (Amendment Act 16 of 2021) enumerating the salient features are reproduced hereinbelow:

“.....The Mines and Minerals (Development and Regulation) Amendment Bill, 2021, inter alia, provides for the following, namely:—

- i) to remove the distinction between captive and merchant mines by providing for auction of mines in future without restriction of captive use of minerals and allowing existing captive mines including captive coal mines to sell up to fifty per cent. of the minerals produced after meeting the requirement of linked end use plants to ensure optimal mining of mineral resources and specify the additional amount to be charged on such sale. The sale of minerals by captive plants would facilitate increase in production and supply of minerals, ensure economies of scale in mineral production, stabilize prices of ore in the market and bring additional revenue to the States;
- ii) to provide for payment of additional amount to the State Government on extension and grant of mining lease of Government companies to create level playing field between the auctioned mines and the mines of Government companies;
- iii) to provide that all the valid rights, approvals, clearances, licences and the like granted to a lessee in respect of a mine shall continue to be valid even after expiry or termination of lease and such clearances shall be transferred and vested to the successful bidder of the mining lease. This will ensure continuity in mining operations even with change of lessee, conservation of mineral and avoid repetitive and redundant process of obtaining clearances again for the same mine;
- iv) to grant short term mining lease to Government companies in situations where the auction of mines pursuant to sub-section (4) of section 8A has failed;
- v) to empower the Central Government to issue directions regarding composition and utilisation of Fund by the District Mineral Foundation;
- vi) to close the pending cases of non-auctioned concession holders which have not resulted in grant of mining leases despite passage of a considerable time of more than five years. The existence of these cases is anachronistic and antagonistic to the auction regime. The closure of the pending cases would facilitate the

Government to put to auction a large number of mineral blocks in the interest of nation resulting in early operationalisation of such blocks and additional revenue to the State Governments;

- vii) to remove the restrictions on transfer of mineral concessions for non-auctioned mines to attract fresh investment and new technology in the sector;
- viii) to empower the Central Government to notify the area and conduct auction in cases where the State Governments face difficulty in notifying the areas and conducting auction or fails to notify the area or conduct auction in order to ensure auction of more number of mineral blocks on regular basis for continuous supply of minerals in the country;
- ix) to fix a time-frame for grant of leases for the areas reserved for Government companies for expediting grant of leases and production by the Government companies; and
- x) to amend section 21 of the Act so as to clarify the expression "without any lawful authority" in order to limit its scope to the violations of the said Act and the rules made thereunder. The said amendment will bring clarity and certainty to the mining sector”.

The following table shows the amendments along with the cross-references

MMDR 2021

Sr. No.	Objective	Amended/Updated Provisions
1	Removal of reservation of mines for end-use of minerals	MMDR Act Sub Section 6 of Section 10B MAR 2015 Sub-Rule 3 of Rule 6
2	Sale of minerals by captive mines	MMDR Act Sub Section 5 of Section 8 Sub Section 7A of Section 8A
3	Auction by the central government in certain cases	MMDR Act Sub Section 3 of Section 10B Sub Section 4 of Section 11
4	Transfer of statutory clearances	MMDR Act Section 8B
5	Allocation of mines with expired leases	MMDR Act Section 8B
6	Rights of certain existing concession holders	MMDR Act Sub Section 2 of Section 10A
7	Extension of leases to government companies	MMDR Act Sub Section 4 of Section 8 MCR Rule 72
8	Conditions for lapse of mining lease	MMDR Act Sub Section 4 of Section 4A
9	Non-exclusive reconnaissance permit	MMDR Act Section 10 C Omitted
10	Composition and utilization of District Mineral Foundation (DMF)	MMDR Section 9-B

MMDR Amendment Act, 2023

In spite of these amendments made by way of amendment Act 16 of 2021, the mineral sector required certain more reforms particularly for increasing exploration and mining of critical minerals that were essential for economic development and national security in the country. The lack of availability of the critical minerals or concentration of their extraction or processing in a few geographical locations were leading to supply chain vulnerabilities and even disruption of supplies. It was felt that the future global economy will be underpinned by technologies that depend on minerals such as lithium, graphite, cobalt, titanium, and rare earth elements. Critical minerals had gained significance in view of India's commitment towards energy transition and achieving net-zero emission by 2070. Therefore, it was felt to further amend the said Act by enacting the Mines and Minerals (Development and Regulation) Amendment Bill, 2023. Accordingly, the Act was amended by an Amendment Act 16 of 2023 on 17th August 2023.

The relevant portion of the Statement of Objects and Reasons of MMDR, 2023 (Amendment Act 16 of 2023) enumerating the salient features are reproduced hereinbelow:

“.....One of the major reforms proposed in the Bill is to introduce exploration licence for deep-seated and critical minerals. The exploration licence granted through auction shall permit the licensee to undertake reconnaissance and prospecting operations for critical and deep-seated minerals mentioned in the newly proposed the Seventh Schedule to the Act. The blocks explored by the exploration licence holder would be auctioned for mining lease within the prescribed timeline, which will fetch better revenue to the State Governments. The exploration agency shall be entitled to a share in the auction premium payable by the mining lease holder. Deep-seated minerals, such as gold, silver, copper, zinc, lead, nickel, cobalt, platinum group of minerals, diamonds, etc. are difficult and expensive to explore and mine as compared to surfacial or bulk minerals and thus share of deep-seated minerals in total mineral production is meager at present. The country is mostly dependent on imports of these minerals. The proposed exploration licence would facilitate, encourage and incentivize private sector participation in all spheres of mineral exploration for critical and deep-seated minerals.

Further, from the list of 12 atomic minerals specified in Part-B of the First Schedule to the Act, it is proposed to omit 6 minerals, namely, (i) Beryl and other beryllium-bearing minerals (ii) Lithium-bearing minerals, (iii) Niobium-bearing minerals, (iv) Titanium bearing minerals and ores, (v) Tantalum-bearing minerals and (vi) Zirconium-bearing minerals and ores. These minerals have various applications in space industry, electronics, communications, energy

sector, electric batteries and are critical in net-zero emission commitment of India. Due to their inclusion in the list of atomic minerals, their mining and exploration is reserved for government entities. Upon removal of these minerals from the said list, exploration and mining of these minerals will be opened up for the private sector as well. As a result, exploration and mining of these minerals is expected to increase significantly in the country.

It is also proposed to empower Central Government to exclusively auction mining lease and composite licence for certain critical minerals listed in new Part-D of the First Schedule to the said Act. As these critical minerals are indispensable for the growth of our economy, authorising the Central Government to auction concession for these critical minerals would increase the pace of auction and early production of the minerals. Even in case of conduct of auction by the Central Government, the mineral concession shall be granted to the selected bidders by the State Government only and the auction premium and other statutory payments shall accrue to the State Government.”

The following table shows the amendments along with the cross-references

MMDR 2023

Sr. No.	Objective	Amended/Updated Provisions
1	Maximum area in which activities are permitted	MMDR Act section 6
2	Auction for exploration licence	MMDR Act Section 10-BA • Validity of exploration licence • Submission of geological reports • Incentive for exploration licensee: MAR Rules 19A, 19B, 19C, 19D, 19E, 19F, 19G, 19H, 19I and 19 J
3	Auction of certain minerals by the central government	MMDR Act Section 11-D
4	Exploration licence for specified minerals	Seventh Schedule under MMDR Act

The Three major waves of Amendments cited hereinabove created a complete paradigm shift in the mineral sector with an intention to bring transparency in the process of grant, enhance share of revenue to the Govt., special impetus on areas and people effected by Mining and boost in the exploration initiatives and special focus on mining of critical minerals from a Strategic National requirement.

Since the amendment in the year 2015, a total of 517 mineral blocks have been successfully auctioned across the country. As Iron ore consist of 78% of the metallic mineral spectrum, the authors have taken a liberty to take Iron Ore as an example to demonstrate the changes happened in this sector in the last 10 years and correlate the same with the Govt. of India's plan with respect to the sector.

Sectoral Impact: Iron Ore Case Study

Auctions and Operationalization

The following table shows the Mining Lease/ Composite License blocks being auctioned, executed and in operation for various minerals.

Particulars	Iron Ore	Others	Total
Blocks Auctioned	140	377	517
Deeds Executed	60	81	141
Mining Lease (ML) Deeds Executed	45	32	77
Composite License (CL) Deeds Executed	15	49	64
Blocks in Operation	40	26	66

Source Ministry of Mines

As it is evident from the above that, despite of all necessary amendments to enable the process of auction and make the auction blocks operate only 28% of the Iron Ore Blocks and 7% of the others are in operation. In other words while the current legal frame work provides for a mechanism to auction blocks with a large amount of participation, falls short in terms of getting them operational.

In addition to the above if we have a glance over the statistics related to Iron ore over the last 10 years in our country, we would be surprise to note that, the “per capita Steel consumption”, “production of Iron Ore” and “production of Steel” has witnessed an average growth of 75%.

Iron & Steel Growth (2015-2030)

The following table shows the Production of Iron Ore, Steel and per capita Steel consumption.

Particulars	2015	2024	2030*
Production of Iron ore (Mtpa)	156	289	437
Production of Steel (Mtpa)	89	150	300
Per capita consumption (kg)	57	97	160

*GDP growth rate assumed by MoS - 7.5% y-o-y

The bare perusal of the figures shows that in spite of no addition of sizable working Iron ore deposits in the portfolio the production rose by 85%. If the remaining 100 auctioned Blocks would have been operational at a notional capacity of 2 MTPA per block the same would have been added another 200 MTPA of Iron ore production to the current production which would have been much above the target set by Ministry of Mines for the year 2030 as shown above.

Operational Bottlenecks

Based on the input of the Industry following are the major impediments in making the blocks operational:

- Permissions and approvals (especially related to EC/FC)
- Fixation of Surface right compensation
- Dedicated corridors/ right of way for various modes of transportation

- Unsustainable premiums of participation
- No incentive for low grade mineral utilization
- High regime of Mineral Tax even after auction

10. Suggestions:

In order to overcome these bottlenecks and impediments mentioned herein above the authors in their limited knowledge and understanding suggests the following measures

- Fast-Track Statutory Clearances :** Currently the industry is facing delays in environment, forest, and land acquisition approvals which stall the mine operations. Following measures to be adopted:

- Implement “Single Window Clearance Portals” at the state level and Mandate deemed approvals within specified timelines post-auction.
- Integrate pre-embedded clearances (EC, FC, land rights).
- Ease Financing and Reduce Entry Barriers:** High upfront payments (auction premiums, performance guarantees) affect the project viability. Following measures are suggested:

- Moratorium on upfront payments and deferred premium schedules
- Facilitate long-tenure mining loans.
- Rationalize Taxation and Compliance Burden:** The current cumulative tax levies (royalty + DMF + NMET + GPIOF/FDT etc) make operations unviable. Following measures are suggested:

- Consider capping on levies total payout $\leq$ 35% of sale value.

- Allow income tax deductions on royalty and DMF payments.

- Strengthening Local Infrastructure:** The current infrastructure specially with respect to transportation etc., is limited and leads to social conflicts and environmental issues. Following measures are suggested:

- Dedicated corridors/railway sidings/pipe conveying for transportation of ore and partner with central schemes (PM Gati Shakti, Sagarmala).

- Leverage District Mineral Foundation (DMF) funds for building these infrastructures

- Operationalize ‘Ready-to-Mine’ Concept:** The current blocks lie idle due to pending development steps post-auction. Following measures are suggested:

- Define and incentivize “Operational within 2 years” norms through contractual obligations.

- b) Reward timely developers with:
- c) Waivers on performance security
- d) Penalize habitual defaulters by blacklisting for re-auction.
- vi) Monitor and Report through Public Dashboards: Lack of transparency in lease operational status. Following measures are suggested:
 - a) Launch a “Mine Progress Dashboard” showing:
 - i) Date of auction and date of lease execution
 - ii) Milestones like EC, FC, land acquisition, production start
 - iii) Include State-wise league tables to boost competition and accountability
 - vii) Align Mining with Local Livelihood and ESG Goals: Community resistance delays land acquisition and mining permissions. Following measures are suggested:
 - a) Use DMF for livelihood enhancement, healthcare, and resettlement of PAPs.
 - b) Mandate Grievance Redress Mechanisms (GRM) at the mine level.
 - c) Build trust through CSR, local hiring, and skill development programs.
 - d) Bonus: Strategic Review of Non-Operational Auctioned Blocks
 - e) Periodically review all auctioned blocks pending operations beyond 2–3 years.
 - f) Conduct Root Cause Analysis (RCA) and consider:
 - g) De-notification or re-auction if blocks are commercially or logistically unviable.
 - h) Offering exit windows for genuine defaulters while maintaining penalties.

(Disclaimer: Views expressed and suggestions given in this article are solely of the authors and the said views in any manner should not be construed as the views of the Company to which they belong to)



Analysis and Impact of the Nine Judge Bench Judgement of the Hon'ble Supreme Court of India in the case of Mineral Area Development Authority (MADA) & ANR. Vs. M/s Steel Authority of India (SAIL) & ANR. Etc. In Civil Appeal Nos. 4056 - 4064 Of 1999, Dated July 25, 2024 & August 14, 2024 on the Mining Industry and way forward...

VIJAY SINGH A R

BE(MIN), FCC(R), FCA

Chartered Accountant

e-mail : arvijaysingh@gmail.com

Synopsis

It is very rare to see a judgment of nine Judge Bench of the Hon'ble Supreme Court on a topic concerning regulation of mines and mineral development. It indeed clarified lot of fundamental issues plaguing the mining industry and also clearly laid down contours of bifurcation of powers between the Central Government and the State Governments and paved the way for greater clarity and in the process allowed the State Governments to come up with newer cesses or other taxes on grant of mineral rights and for holding mineral bearing land under a legitimate mining lease, by concluding that royalty is not a tax and only the States have power to levy cesses or other taxes, since the minerals are found in the land and this subject falls under the exclusive domain of States. The Central Govt. through MMDR Act, 1957 cannot levy taxes or cesses or surcharges on mines & minerals by exercising powers under Entry 54 of List I to Seventh Schedule to the Constitution.

If anybody claims mastery over the MMDR Act, 1957 and its rules then it is mandatory for such a person to thoroughly study (not read) and understand the issues discussed in this 393 page long judgement decided in the ratio of 8 : 1 majority, and in the personal opinion of the author one can get more insights when he studies the dissenting minority judgement given by Justice Mrs. B V Nagarathna and also ought to take cognisance of the review

petition filed by the Central Government and other parties, though the Hon'ble Supreme Court did not entertain and dismissed the review petition.

Apart from bringing clarity in payment of royalty, etc. and division of powers between the Central Government and the State Government/s, it overruled certain judgements rendered by itself in the past and that were holding the field upto now and in the bargain it did not deprive the States of its legitimate collection of cess and other taxes that various State Government/s attempted to levy by virtue of powers conferred under Entry 49 of List I in the Seventh Schedule to the Constitution by allowing the States to collect the state levies that were foregone w.e.f. April 1, 2005 though giving a small reprieve to mining lease holders in terms of defraying the past dues in instalments without interest and penalty.

This judgement is not only important for the mining fraternity, but also for every legal professional who is involved in matters concerning exercise of powers on a particular legislative aspect by the Central Government or State Government.

This article / writeup is divided into following three parts for better appreciation of issues considered and conclusions arrived by the Hon'ble Supreme Court along with its impact and way forward:

Part A - ANALYSIS, DISCUSSIONS AND CONCLUSIONS OF THE HON'BLE SUPREME COURT JUDGEMENT

Part B - IMPACT OF HON'BLE SUPREME JUDGEMENT ON THE MINING INDUSTRY

Part C - WAY FORWARD POST THE HON'BLE SUPREME JUDGEMENT

PART A: ANALYSIS, DISCUSSIONS AND CONCLUSIONS OF THE HON'BLE SUPREME COURT JUDGEMENT

APPEALS / PETITIONS

There were 80 Appeals / Petitions / Transfer Petitions in the matter before the Hon'ble Supreme Court ("Hon'ble Court") beginning from March 30, 2011 when the three Judge Bench of Hon'ble Supreme Court observed that there was conflict between the judgement in India Cement Ltd. and Ors. v. State of Tamil Nadu and Ors., [(1990) 1 SCC 12] delivered by seven Judge Bench of Hon'ble Supreme Court and the judgement in State of West Bengal v. Kesoram Industries Ltd. and Ors, [(2004) 10 SCC 201] delivered by five Judge Bench of Hon'ble Supreme Court and accordingly the matter (Mineral Area Development Authority (MADA) etc. vs. M/s. Steel Authority of India (SAIL) & Ors.) was referred to the nine Judge Bench of the Hon'ble Supreme Court vide order dated March 30, 2011.

INTRODUCTION

The nine Judge Bench judgement was passed in the ratio of 8:1 and the majority verdict was authored by then Chief Justice of India. The judgement as downloaded from the web portal of the Hon'ble Supreme Court runs into 393 pages in the ratio of 200 pages : 193 pages and the questions formulated in the matter were answered by the Hon'ble Court on July 25, 2024 and subsequently on the request of senior counsels, the Hon'ble Court delivered its second verdict on August 14, 2024 in the matter regarding retrospective application of the conclusions reached w.e.f. April 1, 2005.

Subsequent to the majority judgement in the matter, certain parties including the Central Government filed a review petition before the Hon'ble Supreme Court, but the same was rejected by the Hon'ble Court in Diary No. 38926/2024, dated September 24, 2024.

As per the disclosures made to stock exchanges (BSE & NSE) under Regulation 30(4) of the Securities and Exchange Board of India (Listing Obligations and Disclosure Requirements) Regulations, 2015 M/s. Tata Steel Limited has disclosed that it has filed a curative petition in the matter on January 17, 2025 in respect of dismissal of review petition by the Hon'ble Court and the matter is pending before the Hon'ble Court.

ORIGIN OF LIS i.e. LITIGATION

Litigation in the case of India Cement Limited

- Under Section 115 of the Madras Panchayats Act (XXXV of 1958), as amended by Madras Act XVIII of 1964, the appellant i.e. M/s. India Cement Limited was required to pay local cess @ 45 paise per rupee of land revenue and the said imposition was with retrospective effect along with local cess surcharge under section 116 of the Act. An explanation was also inserted in the said Act to construe that land revenue includes royalty paid by the miners from the mineral excavated from the land.

- This levy of cess was challenged by India Cement by taking a stand that royalty was itself a tax and there cannot be levy of tax on tax by way of levy of cess on land revenue that includes royalty in Writ Petition No. 1864/65 before the Hon'ble High Court of Madras (Single Judge). Order passed on February 23, 1967 and the levy upheld.

- M/s. India Cement filed an appeal in W.A. No. 464 of 1967 before the Hon'ble High Court of Madras (DB). By Judgment and Order dated October 13, 1969 the Division Bench of the Hon'ble High Court of Madras upheld the Single Judge Bench Order (supra).

- The Hon'ble High Court of Madras upheld the levy of cess by the State Government by relying on Entry No. 49 to List II of Seventh Schedule of the Constitution.

- Being aggrieved, M/s. India Cement filed an appeal in Civil Appeal No. 62 (N) of 1970 before the Hon'ble Supreme Court, which was subsequently referred to seven Judge Bench of the Hon'ble Supreme Court.

- M/s. India Cement argued that the MM(D&R) Act, 1957 ("MMDR Act") is a comprehensive code for the regulation of mines and development of minerals and section 9 provides that the holder of a mining lease shall pay royalty in respect of any mineral removed or consumed from the leased area at the specified rates and royalty itself is a tax and the state legislatures lack competence to levy taxes on mineral rights because the subject-matter is covered by the MMDR Act.

- The seven Judge Bench of the Hon'ble Supreme Court in its judgement dated October 25, 1989 has held that -

- (i) the state legislature is not competent to impose cess / tax on royalty. The Hon'ble Supreme Court invalidated the cess on land levied with reference to the value of minerals underlying in such land.

- (ii) the Hon'ble Supreme Court concluded that royalty is a tax, and as such a cess on royalty being a tax on royalty, is beyond the competence of the State Legislature because section 9 of the MMDR Act covers the field and the State Legislature is denuded of its competence under Entry 23 of List II.

(iii) with respect to Entry 49 of List II, the Hon'ble Supreme Court observed that royalty is directly relatable to the minerals extracted and therefore would only be relatable to Entries 23 and 50 of List II, and not entry 49 of List II.

- The Hon'ble Supreme Court in *India Cement*, however, directed that the said decision shall only have a prospective effect. This was for the reason that the States had been levying and collecting the cesses on the basis of an earlier decision of the Hon'ble Supreme Court in *HRS Murthy vs. Collector of Chittoor*, AIR 1965 SC 177.

Subsequent decisions of the Hon'ble Supreme Court based on India Cement seven Judge Bench Judgement

- A three Judge Bench of the Hon'ble Supreme Court in *Orissa Cement Ltd. Vs. State of Orissa* [(1991) Supp I SCC 430 [36]], dated April 4, 1991 declared identical levies imposed by the States of Orissa, Bihar and Madhya Pradesh as being lacking in legislative competence (para 26.1 of majority judgement refers).

- The Bench again directed that the said decision shall be operative prospectively with effect from the date of the said judgment i.e. April 4, 1991 in the case of *State of Bihar*, w.e.f. December 22, 1989 in the case of *State of Orissa* and w.e.f. March 28, 1989 in the case of *State of Madhya Pradesh* (para 26.2 of majority judgement refers).

- Based on the seven Judge Bench judgement of the Hon'ble Supreme Court in the *India Cement* case, several Hon'ble High Courts stayed / quashed the levy of cess or surcharge on minerals and the *India Cement* decision held the field for a very long time.

Litigation in the case of Kesoram Industries Limited

- The Cess levied by State of West Bengal under Cess Act of 1880, Education Cess levied under West Bengal Primary Education Act, 1973 and Rural Employment Cess levied under West Bengal Rural Employment & Production Act, 1976 (as amended on 1992) were under challenge before the Hon'ble Calcutta High Court by M/s. *Kesoram Industries Limited & Ors.*

- The Division Bench of the Hon'ble Calcutta High Court, relying on the seven Judge Bench Judgement in *India Cement* matter, struck down Cesses (Road Cess and Public Works Cess, etc.) on coal bearing & other lands vide Judgement dated November 25, 1992 [AIR 1993 Calcutta 78] w.e.f. April 1, 1992.

- The State of West Bengal filed an appeal before the Hon'ble Supreme Court against the aforesaid judgement rendered by the Hon'ble Calcutta High Court. On October 12, 1999 the three Judge Bench of the Hon'ble Supreme Court referred the matter to a Constitutional Bench (five Judge Bench) and thus the matter came to be referred as *The State of West Bengal vs. Kesoram Industries Ltd. and*

Ors. In Appeal (civil) 1532-1533 of 1993, the matter was taken up and heard by the five Judge Bench of the Hon'ble Supreme Court and judgement delivered on January 15, 2004 in a ruling decided in the ratio of 3:2 majority.

- The five Judge Bench of the Hon'ble Supreme Court concluded that the State legislature is competent to impose cess / tax and that there was typographical error in earlier seven Judge Bench judgment of *India Cement* (specifically in para 34). Accordingly, the Hon'ble Supreme Court upheld the cess imposed by State of West Bengal in this case.

- Further the Constitution Bench held that the decision in *India Cement* stemmed from an inadvertent error and clarified that royalty is not a tax.

- Interim, the Hon'ble High Court of Allahabad has upheld the constitutional validity of cess levied in the State of U.P. on minor minerals which decisions are the subject-matter of civil appeals filed under Article 136 of the Constitution before the Hon'ble Supreme Court. Date of Judgement – 01.03.2000 (*Ram Dhani Singh Vs. Collector, Sonbhadra and Ors.* - AIR 2001 Allahabad 5) - Section 35 of the U.P. Special Area Development Authorities Act, 1986, r/w Rule 3 of the Shakti Nagar Special Area Development Authority (Cess on Mineral Rights) Rules, 1997.

Referring to larger bench of nine member bench of the Hon'ble Supreme Court

- The Hon'ble High Court of Patna (now Jharkhand) in *CWJC 1885/1994* in the case of *SAIL vs. State of Bihar* and 10 others held the cess imposed on land being used for mining was not within the scope of Entry 49 of List II to Seventh Schedule of the Constitution and hence State Government cannot impose cess. Date of Judgement March 22, 1999. The Hon'ble High Court relied on *India Cement* judgment of the Hon'ble Supreme Court.

- The judgment of Hon'ble High Court was challenged before the Hon'ble Supreme Court by the State Government titled as *Mineral Area Development Authority Vs. Steel Authority of India Ltd. (MADA vs. SAIL)* (Civil Appeal No. 4056-4064 of 1999).

- On March 30, 2011 - *MADA vs. SAIL* came up for hearing before three Judge Bench of Hon'ble Supreme Court and the Hon'ble Court observed that there is conflict between *India Cement* judgment (Seven Judge Bench) and *Kesoram* judgment (five Judge Bench) and accordingly the matter was referred to nine Judge Bench vide order dated 30.03.2011 by formulating a set of questions to be decided by the larger bench.

LEGISLATIONS PROMULGATED ACROSS THE COUNTRY BY VARIOUS STATE GOVERNMENTS PRIOR TO INDIA CEMENT JUDGEMENT AND POST KESORAM INDUSTRIES JUDGEMENT OF THE HON'BLE SUPREME COURT

State enactments levying Cess (prior to India Cement Case) – Alphabetical order

- 1) The Andhra Pradesh (Mineral Rights) Tax Act, 1975 (A.P. Act 14 of 1975).
- 2) The Andhra Pradesh (Andhra Area) District Boards Act, 1920.
- 3) The Andhra Pradesh (Telengana Area) District Boards Act, 1955.
- 4) The Cess Act, 1880 (Bengal Act 9 of 1880) as applicable in the State of Bihar.
- 5) The Karnataka Zilla Parishads, Taluk Panchayat Samitis, Mandal Panchayats and Nyaya Panchayats Act, 1983 (Karnataka Act 20 of 1985).
- 6) The Karnataka (Mineral Rights) Tax Act, 1984 (Karnataka Act 32 of 1984).
- 7) The Madhya Pradesh Karadhan Adhiniyam, 1982 (M.P. Act 15 of 1982).
- 8) The Madhya Pradesh Upkar Adhiniyam, 1981 (M.P. Act 1 of 1982).
- 9) The Maharashtra Zilla Parishads and Panchayat Samitis (Amendment and Validation) Act, 1981 (Maharashtra Act 46 of 1981).
- 10) The Orissa Cess Act, 1962 (Orissa Act II of 1962).
- 11) The Tamil Nadu Panchayat Act, 1958 (Tamil Nadu Act XXXV of 1958).

- Certain state enactments were struck down by the Hon'ble High Courts. Eg. the Hon'ble High Court of Karnataka declared the Karnataka (Mineral Rights) Tax Act, 1984 as unconstitutional when the constitutional validity was questioned in the case of M/s. Evershine Monuments & Ors. in WP Nos. 14360/84, 15922/84, 16053/84, 17076/84 and 17385/84 in its judgement dated 12.09.1990 by squarely relying on the Hon'ble Supreme Court judgement in India Cement case.

- The seven Judge Bench judgement of the Hon'ble Supreme Court in the case of India Cement had practically rendered the above state enactments otiose and the states could not have collected any cess or other levies on minerals or mineral bearing lands or on royalty, apart from royalty as per section 9 of the MMDR Act. The India Cement judgement had rendered the collection of cess, etc. by the State Government through the above said State enactments without authority of law and the same is barred under Article 265 of the Constitution.

- Practically the state Governments had to refund the cesses or other levies collected to the person who has borne the incidence or made payment to the State exchequer. In addendum the states' financial position was

precarious and refund of unauthorisedly collected cesses or levies would cast a huge financial burden on the State Governments.

- Hence the Central Government enacted "The Cess and Other Taxes on Minerals (Validation) Ordinance, 1992 (Ord. 7 of 1992)" that was promulgated by the President of India on February 15, 1992, to validate collection of such levies by State Governments up to the 4th day of April, 1991 (cut-off date considered since the Hon'ble Supreme Court passed judgement in the Orissa Cement Limited on this date which struck down the levy under The Orissa Cess Act, 1962, by following the ratio laid down in the India Cement judgement).

- The Cess and Other Taxes on Minerals (Validation) Act, 1992 [Act No. 16 of 1992] ("Validation Act") was Gazetted on April 4, 1992 w.e.f. February 15, 1992 by the Central Government. In the preamble the Central Government stated as under:

An Act to validate the imposition and collection of cesses and certain other taxes on minerals under certain State laws.

- The dominant objective of the Validation Act was to validate the levies already made upto April 4, 1991, and not to legislate on the subject by naming a law imposing cess on royalty.

- The Validation Act had just three (3) sections with one Schedule comprising the above said eleven (11) state enactments. The main purpose of the Validation Act was to safeguard the collections already made by the State Government/s in the name of cess or other taxes under the aforesaid eleven (11) state enactments upto April 4, 1991 and to curb collection of cesses and other taxes thereafter.

- The Parliament took precaution to itself re-legislate on the subject matter in exercise of its legislative power and it chose to legislate by incorporation, a method of legislation well recognised by law. The technique may be called archival drafting because it requires persons applying the Act after a considerable period has elapsed since the relevant date to engage in historical research in order to find out what the law thus imported amounts to.

- The Parliament had power to legislate on the topic it could make an Act on the topic by any drafting means including by referential legislation.

- The Cess and Other Taxes on Minerals (Validation) Act, 1992 was under challenge before a two (2) Judge Bench of the Hon'ble Supreme Court in the case of P. Kannadasan and Ors. v. State of Tamil Nadu and Ors. ([1996] 5 SCC 670) and the Hon'ble Supreme Court upheld the powers conferred on the Central Govt. to promulgate the Validation Act by its judgement dated July 26, 1996.

- Interim an issue arose in the State of Bihar, wherein the state relying on the Validation Act, 1992 was seeking to collect the cess & other levies that were not collected upto April 4, 1991 and the same was challenged by TISCO (Tata Iron and Steel Company Limited) (re-christened as Tata Steel Limited now) & Others before the Hon'ble Patna High Court in C.W.J.C. Nos. 1280, 1507, 1639, 1702, 1711 and 1870 of 1992 (R) and the Hon'ble Patna High Court did not allow the State Govt. to collect the cess & other levies that remain un-recovered vide its judgement dated January 17, 1996. The Hon'ble Patna High Court never had the benefit of relying on the two Judge Bench judgement of the Hon'ble Supreme Court in the case of P. Kannadasan and Ors. v. State of Tamil Nadu and Ors. (supra), since the judgement was delivered later on July 26, 1996.

- Aggrieved, the State of Bihar filed an appeal before the Hon'ble Supreme Court against the aforesaid judgement of the Hon'ble Patna High Court in DISTRICT MINING OFFICER AND ORS. vs. TATA IRON AND STEEL CO. AND ANR. [Civil Appeal Nos. 4803- 4808 of 2001] and the matter was posted before the three (3) Judge Bench of the Hon'ble Supreme Court and the Hon'ble Court upheld the judgement and order of the Hon'ble Patna High Court by reasoning that the Validation Act, 1992 protected only the amounts already collected by the State Governments through invalid laws, but it never gave powers to the State Government/s to collect / recover any amount that was pending collection / recovery upto April 4, 1991.

- The Hon'ble Supreme Court in the TISCO matter held that the expression "imposition and collection" would mean, imposition already made or collection already made under certain State laws and the preamble cannot be construed to mean to confer a further right of imposition and collection of cesses on the minerals extracted up to 4th April, 1991.

- Benefit of litigation to M/s. India Cement Limited in terms of non payment of cess & surcharge - India Cement Limited had challenged the levy of cess, right from the date of inception of the levy under the Tamil Nadu Act and the Hon'ble High Court of Madras had granted stay of the operation of the Act. Even after the judgment of the Hon'ble High Court, while the matter was pending in the Hon'ble Supreme Court in appeal, the stay order was operating and the assessee, therefore, never passed on the cess levied to any consumer nor could it do so because the commodity was a controlled commodity and the litigation ended with a judgment in favour of the assessee. The Hon'ble Supreme Court reasoned that to re-open such cases in the garb of the Validation Act and seeking to impose levy and collection from the year 1964 would not only be unreasonable, but also would be contrary to the very judgment passed inter-parties and the Court having stayed the operation of the Act in favour of the assessee.

State enactments levying Cess & other taxes (post Kesoram Industries Case) – Alphabetical order

Pursuant to Kesoram judgment various States enacted fresh laws imposing cess / tax. Some of the Acts are:

- 1) Bihar Coal Mining Area Development Authority (Amendment) Act, 1992 and the Bihar Mineral Area Development Authority (Land Use Tax) Rules, 1994.
- 2) Orissa Rural Infrastructure and Socio-economic Development Act, 2004.
- 3) Chhattisgarh (Adhoshanrachna Vikas Evam Paryavaran) Upkar Adhiniyam, 2005 (No.7 of 2005).
- 4) Madhya Pradesh Rural Infrastructure and Road Development Act, 2005.
- 5) Telangana Mineral Bearing Lands (infrastructure) Cess Act, 2005 (Act No. 38 of 2005).
- 6) Andhra Pradesh Mineral Bearing Lands (infrastructure) Cess Act, 2005 (Act No. 38 of 2005).
- 7) Environment and Health Cess on Mineral Rights under Section 16 of the Rajasthan Finance Act, 2008.
- 8) Jharkhand Mineral Bearing Lands (Covid-19 Pandemic) Cess Act, 2020.

- In certain cases the above state enactments were challenged before the Hon'ble High Courts and certain Hon'ble High Courts granted stay of levy of cess and other taxes by relying on the seven (7) Judge Bench order in India Cement case and not on the five (5) Judge Bench ruling in Kesoram Industries case, following the judicial hierarchy. Eg. The Hon'ble Orissa High Court stayed operation of Orissa Rural Infrastructure and Socio-economic Development Act, 2004 and never allowed the State of Orissa to collect the cess & other taxes under this enactment.

CONSIDERATION OF FACTORS ALONG WITH REASONING, DISCUSSIONS AND CONCLUSIONS ARRIVED BY THE MAJORITY IN THE NINE JUDGE BENCH OF THE HON'BLE SUPREME COURT IN MADA & ANR. VS. SAIL & ANR.

- **Basics of Constitution** - The Indian Constitution, as amended by the 106th Constitution Amendment Act, 2023 has 448 articles in 22 parts along with 12 Schedules. The Hon'ble Court has clearly opined that the Indian written Constitution has virtually become permanent owing to the judgement delivered by the thirteen (13) Judge Bench in the case of Kesavananda Bharati v. State of Kerala (1973) 4 SCC 225 [582] by a majority ruling of 7:6. The Hon'ble Supreme Court has clearly held that the basic structure of the Constitution can never be amended / altered by the law makers.

• In the same judgement the Hon'ble Supreme Court has recognised that federalism embodies a division of powers between the units of the federation, that is, the Union and the States. Indian federalism is defined as asymmetric because it tilts towards the Centre, producing a strong Central Government. Yet, it has not necessarily resulted in weak State Governments.

• Fiscal federalism entails that the power of the States to levy taxes within the legislative domain carved out to them and subject to the limitations laid down by the Constitution must be secured from unconstitutional interference by Parliament (para 54 of the majority judgement, refers).

• Article 245 (read with Article 246) of the Constitution is the source of the legislative powers of Parliament / Central Govt. and the State legislatures / State Legislatures. The Hon'ble Court looked into the powers bestowed under the Constitution to the Parliament and the State legislatures in connection with enactment of statutes and the powers to levy tax as mentioned in the Seventh Schedule to the Constitution.

• The Seventh Schedule has three (3) lists – List I (Union List), List II (State List) and List III (Concurrent List). The entries mentioned in List I, only the Parliament can legislate and for entries mentioned in List II, only the State Legislatures can legislate and for entries mentioned in List III, both of them can legislate without encroaching each other areas, if already legislated by one of them.

• In Para 38 (majority ruling) the Hon'ble Court has mentioned that the structure of the legislative entries in the three Lists of the Seventh Schedule follows an express and deliberate pattern. The entries are classified into general and taxing entries (R Abdul Quader & Co. v. STO, (1964) 6 SCR 867, [8]).

• The entries in the Seventh Schedule to the Constitution can be grouped as under:

Particulars	List I	List II	List III
Total no. of entries	1 to 97 [98 Entries]	1 to 66 [59 Entries]	1 to 47 [52 Entries]
Regular / general Entries	1 to 81	1 to 44	1 to 46
Taxing Entries (incl. stamp duties)	82 to 92B	45 to 63	No Entries for taxation
Other entries	93 to 95	64 to 65	----
Entries dealing with fees	96	66	47
Residuary Entry	97	---	----

• The Hon'ble Supreme Court in the case of M.P. V. Sundaramier & Co. vs. The State of Andhra Pradesh & Ors. [1958 AIR 468], date of judgement 11th March, 1958 has clearly spelt out the distinction between regular / general entries and taxing entries in the three (3) Lists of Seventh Schedule to the Constitution. It also gave illustrations as under in this judgement:

Illustrations - List I Union List	Illustrations - List II State List
Entry 22 in List I is "Railways", and Entry 89 is "Terminal taxes on goods or passengers, carried by railway, sea or air; taxes on railway fares and freights". If Entry 22 is to be construed as involving taxes to be imposed, then Entry 89 would be superfluous.	Entry 18 of List II, is "Land" and Entry 45 is "Land Revenue."
Entry 41 mentions "Trade & commerce with foreign countries; import and export across customs frontiers;". If these expressions are to be interpreted as including duties to be levied in respect of that trade and commerce, then Entry 83 which is "Duties of customs including export duties" would be wholly redundant.	Entry 23 is "Regulation of mines" and Entry 50 is "taxes on mineral rights"
Entries 43 and 44 relate to incorporation, regulation and winding up of corporations. Entry 85 provides separately for Corporation tax.	----

• Under the scheme of the Entries in the Lists of Seventh Schedule, taxation is regarded as a distinct matter and is separately set out. The legislature does not derive the power to tax from the general entries - taxation is considered to be a distinct matter for purposes of legislative competence (Para 38 of majority ruling refers). Para 39 of the majority ruling, the Hon'ble Court mentions that if a taxing power is enumerated within a particular legislative list, it is automatically excluded from the purview of subject-matters in other legislative lists. The above position of law has been expressly affirmed by the nine-Judge Bench of the Hon'ble Supreme Court in Jindal Stainless Ltd v. State of Haryana [(2017) 12 SCC 1 [617]].

• Entries relating to taxing powers must be construed with clarity and precision to maintain exclusivity and a construction of a taxation entry which may lead to overlapping must be eschewed (Godfrey Phillips India Ltd. v. State of UP, (2005) 2 SCC 515 [46]). Para 40 of the majority judgement - The rule that words should receive their ordinary, natural, and grammatical meaning applicable to statutes also applies to the entries contained in the Seventh Schedule (Navinchandra Mafatlal v. Commissioner of Income Tax, Bombay City, (1954) 3 SCC 623).

• The Hon'ble Supreme Court in para 41 of the majority judgement has categorically held that any invasion by Parliament in the field assigned to the States and vice versa is a breach of the Constitution. In Para 54 of the majority judgement the Hon'ble Supreme Court has held that fiscal federalism entails that the power of the States to levy taxes within the legislative domain carved out to them and subject to the limitations laid down by the Constitution must be secured from unconstitutional interference by Parliament.

• The Hon'ble Supreme Court in the light of above discussions arrived at a conclusion that the Parliament in exercise of Entry 54 of List I has framed the MMDR Act, 1957, which is a regular / general entry and Entry 54 of List I

does not grant power to the Parliament / Central Govt. to levy taxes whatsoever on extraction of minerals or on award of mineral rights in lands. Entry 23 of List II also talks about regulation of mines and mineral development, but is made subordinate to Entry 54 of List I. Hence MMDR Act, 1957 promulgated by the Central Govt. holds the field of regulation of mines and minerals development till date. For better appreciation Entry 54 of List I and Entry 23 of List II are mentioned as herebelow:

- Entry 54 of List I - Regulation of mines and mineral development to the extent to which such regulation and development under the control of the Union is declared by Parliament by law to be expedient in the public interest.
- Entry 23 of List II - Regulation of mines and mineral development subject to the provisions of List I with respect to regulation and development under the control of the Union.
- The fact of exercising powers under Entry 54 of List I by the Union is mentioned in section 2 of the MMDR Act, 1957.
- The readers may have a confusion that if the Union has formulated the MMDR Act, 1957 under Entry 54 of List I, then why are the concession rules of minor minerals framed by the State Government/s? This is a very valid query, more-so in the background of Entry 23 of List II.
- Section 15 of the MMDR Act, 1957 has given powers to the State Governments to frame their own rules in connection with grant, administration, royalty payments, etc. of concessions of minor minerals, once the Central Govt. notifies a particular mineral as minor mineral under section 3(e) of the MMDR Act, 1957. Hence each of the states in India have their own minor mineral concession rules. At no point in time it should be construed that minor mineral concession rules are emanating owing to the powers given to the state legislature under Entry 23 of List II. As a matter of fact, no State Government till date has exercised any power under Entry 23 of List II.

What is Royalty?

- Once the Hon'ble Supreme Court was convinced about the exercise of powers under Entry 54 of List I to the Seventh Schedule of the Constitution by the Central Govt., it turned its attention to differences between lease and licence. In Para 85 of majority judgement, the Hon'ble Supreme Court referred to its decision in the Associated Hotels of India Ltd vs. R N Kapoor ((1960) 1 SCR 368, [28]) and concluded that a lease creates an interest in property, while a licence only permits another to make use of the property, whose legal possession continues to remain with the owner. A lease envisages and transfers an interest in the demised property creating a right in rem in favour of the lessee, while a licence only makes an action lawful which without it would be unlawful (Mangal Amusement Park Private Ltd. vs. State of Madhya Pradesh, (2012) 11 SCC

713 [15]). The Hon'ble Court also took cognisance of Section 3(26) of the General Clauses Act 1897, Section 2(6) of the Registration Act & Section 105 of the Transfer of Property Act 1882 to conclude as above.

- Under a lease deed for mining operations, the owner transfers the interest in the minerals to the lessee in lieu of the payment of rent, which usually takes the form of royalty (para 88 of majority judgement refers). Royalty is generally understood as compensation paid for rights and privileges enjoyed by the grantee (para 94 of majority judgement refers).
- The Hon'ble Supreme Court looked into the nature of mining lease under the MMDR, 1957 and the Mineral Concession Rules, 1960 (MCR, 1960). The Hon'ble Court referred to its earlier decision in the case of State of Meghalaya v. All Dimas Students Union, ((2019) 8 SCC 177 [129]-[130]) and held that there are specific provisions in the MCR, 1960 concerning sanctioning of mining lease where minerals vest in the Government, and separate provisions where minerals vest in private persons and when minerals vest partly with Government and partly with private persons. The Hon'ble Court concluded that when minerals are owned by the private persons and in such a case if a mining lease is to be granted then it shall be deemed to have been granted by such private persons or under authority of such private owners.
- In the light of above provisions in the MMDR Act, 1957 and MCR, 1960 the Hon'ble Court turned its attention to Article 366(28) which defines "taxation" to include "the imposition of any tax or impost, whether general or local or special." This Court has interpreted the word "tax" in its widest amplitude to include all money raised by taxation. In Jindal Stainless Steel the Hon'ble Court held that the expression "any tax" means "any levy which the State is constitutionally competent to legislate.
- Para 106 of the majority judgement – The Hon'ble Court has generally construed the expression "imposts" to include taxes and fees [CCE v. Chhata Sugar Co. Ltd., (2004) 3 SCC 466 [36] (It was observed that an impost can be either a tax or fee.)] realizable by the authority of law [Indian Banks' Association v. Devkala Consultancy Service, (2004) 11 SCC 1 [18]]. The Central Government and the Respondents were also harping on considering royalty as a statutory exaction and is compulsory in nature and hence akin to tax. In CIT v. McDowell and Co. Ltd. [(2009) 10 SCC 755 [22]], the Hon'ble Supreme Court held that the term "impost" means compulsory levy and that "tax" in its wider sense includes all imposts.
- The Hon'ble Supreme Court also referred to certain Hon'ble High Court decisions qua royalty interpretation. The Hon'ble Gujarat High Court in the case of Saurashtra Cement & Chemical Industries Ltd. vs. Union of India (1979 SCC OnLine Guj 23) held that royalty payable under Section

9 of the MMDR Act, 1957 was not a tax. Therefore, Parliament had legislative competence to prescribe royalty under the MMDR Act in pursuance of its regulatory powers under Entry 54 of List I. The Hon'ble Orissa High Court in the case of *Laxmi Narayan Agarwalla vs. State of Orissa* (1983 SCC OnLine Ori 16) held if royalty is held to be tax, section 9 of the MMDR Act, 1957 would have to be invalidated because Parliament has no legislative power to impose tax under Entry 54 of List I. In *AIR 1969 Punj and Har 79*, the Hon'ble Punjab and Haryana High Court in *Dr. Shanti Swaroop Sharma vs. State of Punjab* rejected the contention of the Petitioners that royalty, being a tax, cannot be levied under delegated legislation.

- In *Quarry Owners Association vs. State of Bihar*, the Hon'ble Supreme Court held that royalty "does not constitute usual tax as commonly understood" but includes return for the consideration for parting with the property ((2000) 8 SCC 655 [34]).

- In *Kesoram*, the Constitution Bench of the Hon'ble Supreme Court had to decide on the validity of a cess levied by the State on coal-bearing land. The measure of the cess was relatable to the quantity of minerals produced from land. Whether royalty is a tax was not directly in issue and also held that *India Cement* was distinguishable because in that case cess was levied on royalty and not on mineral rights or lands. The decision in *Kesoram* (supra) analyzed the nature of royalty to hold that royalty is not a tax, but a payment made to the owner of land who may be a person and may not necessarily be the state (para 121 of the majority judgement refers).

- The Hon'ble Supreme Court finally concluded that Royalty is not a tax. The Hon'ble Court reasoned that on first principles, royalty is a consideration paid by a mining lessee to the lessor for enjoyment of mineral rights and to compensate for the loss of value of minerals suffered by the owner of the minerals. The liability to pay royalty arises out of the contractual conditions of the mining lease. A failure of the lessee to pay royalty is considered to be a breach of the terms of the contract, allowing the lessor to determine the lease and initiate proceedings for recovery against the lessee (para 123 of majority judgement refers).

- In para 126 of the majority judgement the Hon'ble Supreme Court laid out the differences between royalty and tax as herebelow:

Royalty	Tax
(i) The proprietor charges royalty imposition as a consideration for parting with the right to win minerals.	(i) Tax is an of a sovereign.
(ii) Royalty is paid in consideration of doing a particular action, i.e. extracting minerals from the soil.	(ii) Tax is generally levied with respect to a taxable event determined by law.
(iii) Royalty generally flows from the lease deed.	(iii) Tax is imposed by authority of law.

- Para 127 of the majority judgement - Under the MMDR Act, the Central Govt. fixes the rates of royalty, but it is still paid to the proprietor by virtue of a mining lease. In case the minerals vest in the Government, the mining lease deed is signed between the State Government (as lessor) and the lessee in pursuance of Article 299 of the Constitution. Through the mining lease, the Government parts with its exclusive privilege over mineral rights. A consideration paid under a contract to the State Government for acquiring exclusive privileges cannot be termed as an impost. Since royalty is a consideration paid by the lessee to the lessor under a mining lease, it cannot be termed as an impost.

- In para 130 of the majority judgement, the Hon'ble Supreme Court concludes that both royalty and dead rent do not fulfil the characteristics of tax or impost. Accordingly, the Hon'ble Court concludes that the observation in *India Cement* (supra) to the effect that royalty is a tax is incorrect.

Inter-relationship between Entry 50 of List II and Entry 54 of List I.

Exact wordings of Entry 54 of List I is already mentioned above. The text of Entry 50 of List II is as under:

"Taxes on mineral rights subject to any limitations imposed by Parliament by law relating to mineral development."

- As already explained above, Entry 50 is a taxing entry and not a regular or general legislative entry. Meaning thereby that if taxes on mineral rights have to be levied, it shall be levied only by the State Government/s and not by the Central Governments, of course subject to any limitations imposed by Parliament by law relating to mineral development i.e. MMDR Act, 1957.

- Before dwelling on other aspects of taxes on mineral rights, the Hon'ble Supreme Court in para 173 of the majority judgement, referred to the *Black Law's* dictionary meaning of mineral rights, wherein it defines "mineral right" as "an interest in minerals in land, with or without ownership of the surface of the land; a right to take minerals or a right to receive royalty."

- It also referred to its earlier decision in the case of *Thressiamma Jacob vs. Geologist, Department of Mining & Geology*, ((2013) 9 SCC 725) and held that in the context of land, it is well-established that the ownership of land includes the ownership of underlying minerals, unless the right to minerals has been expressly reserved by law.

- In Para 259 of the majority judgement, the Hon'ble Supreme Court in *Raja Anand Brahma Shah vs. State of U P* (1966 SCC OnLine SC 89 [13]) a Constitution Bench accepted that the English system of ownership of lands applied in India, observing that the owner of the surface of land is entitled ex-jure to everything beneath the land. It was further observed that a transfer of the right to the surface

conveys the right to the minerals underneath unless there is an express or implied reservation in the grant of land.

- Ownership of Minerals – Entry 18 in List II. The Hon'ble Supreme Court took cognisance of the legislative power of States to enact land legislation that can be traced to Entry 18 of List II which empowers the State legislatures to legislate with respect to matters dealing with “land, that is to say, rights in or over land, land-tenures including the relation of landlord and tenant, and the collection of rents. After Independence, the State legislatures enacted land reform legislation divesting land owners of their sub-soil rights, including rights in the minerals (paras 260 & 261 of majority judgement refers).

- Para 263 of the majority judgement, the Hon'ble Supreme Court observed that “Rights in minerals generally follow ownership of the land”. The right of an owner of land extends to the sub-soil, including the minerals found underneath the soil, which continues until the State deprives the owner by a valid legal process. Importantly, Section 16(I)(b) of the MMDR Act also recognizes that the rights to minerals does not automatically vest in the State Government.

- The Hon'ble Supreme Court in para 268 of the majority judgement, gave credence to the fact that, first the owner of a land can be divested of sub-soil rights in minerals only through a valid process of law, which has generally taken the shape of land reform legislation enacted by State legislatures. Second, the MMDR Act does not vest the ownership of minerals or mineral rights in the State. It regulates the exercise of rights to minerals which may be owned either by Government, private persons, or by both the Government and private persons.

- It illustrates certain state enactments where the right to minerals in private lands have been taken over or vests in the State Government/s –

- i. Section 48 of the Maharashtra Land Revenue Code 1966
- ii. Uttar Pradesh Zamindari Abolition and Land Reforms Act 1950.
- iii. Section 3 of the Haryana Minerals (Vesting of Rights) Act 1973.
- iv. Gujarat Land Revenue Code 1879, Section 69A.
- v. Madhya Pradesh Land Revenue Code 1959, Section 247.
- vi. Chhattisgarh Land Revenue Code 1959, Section 247.
- vii. Goa, Daman and Diu Land Revenue Code 1968, Section 36.
- viii. Section 70 of the Karnataka Land Revenue Act, 1964 (not mentioned in the judgement)

- To a question whether the States can come up with a legislation vesting ownership rights in the State Governments despite the field being governed by the MMDR Act, 1957? The Hon'ble Supreme Court referred to its own decision in the State of Haryana vs. Channan Mal [(1977) 1 SCC 340], that lays down the principle that the decision of the States to acquire title to minerals does not fall foul of the MMDR Act because the latter does not control the ownership of minerals.

- The Hon'ble Supreme Court in the light of above discussions has unambiguously held that royalty is paid to the proprietor of the minerals for the exercise of mineral rights. Subsoil minerals can either be legally vested in the States or continue to remain vested with private landowners. Resultantly, the payment of royalty under Section 9 of the MMDR Act is paid either to the State Government or private landowner, as the case may be (para 266 of majority judgement refers).

- A mining lease contemplated under the MMDR Act relates to the mining rights and mineral rights. It does not grant surface rights to the mining lessee (para 320 of majority judgement refers).

Union can impose Limitations on powers of State to tax mineral rights under entry 50 of List II

- The expression “any limitations” in Entry 50 of List II is indicative of the fact that Parliament has been provided with ample legislative freedom to conceive limitations or restrictions on the legislative powers of the State to tax minerals. As a matter of fact this is only entry in the Seventh Schedule where the powers have been given to the Parliament to restrict or impose limitations on a taxing entry reserved for State Government/s. Hence Entry 50 of List II is SUI-GENERIS i.e. unique or class apart in the Scheme of Seventh Schedule to the Constitution.

- The legislative domain to tax mineral rights vests with the State. The legislative power of Parliament to impose “any limitations” is traced to Article 246(I) read with Entry 54 of List I. Parliament can impose limitations, and not levy taxes on mineral rights itself. The subject of taxing mineral rights continues to remain with the States. This understanding also ensures that there is no overlap or conflict between the powers of Union and the taxing field of the States.

- To question posed to the Hon'ble Supreme Court, does the expression “any limitations” include the power to prohibit States from taxing mineral rights? The Hon'ble Court asserted that, we are of the opinion that the answer must be in the affirmative (para 244 of the majority judgement refers).

- Para 245 of the majority judgement – The overall scheme of Article 246 read with Entry 54 of List I and Entry 50 of List II makes it clear that Parliament, in the interests of mineral

development, can impose “any limitations.” The purport of the expression “any limitations” is wide enough to include the imposition of restrictions, conditions, principles, as well as prohibition. Parliament has the constitutional power to determine whether and if so the manner in which limitations may be imposed.

- In para 224 of the majority judgement, the Hon'ble Supreme Court mentions that there is no specific provision in the MMDR Act which imposes limitations on the power of the States to tax mineral rights.
- Entry 50 of List II does not result in the field of taxing mineral rights being conferred on Parliament. This is clear also because there is no specific entry in List I giving the field of taxing mineral rights to the Union.
- Exception to the Sundararamier principle - Entry 50 of List II is not an exception to the Sundararamier principle (supra) which is that taxing entries are enumerated separately from the general entries in Lists I and II of the Seventh Schedule. The field of taxation cannot be derived from regulatory legislative entries and has to be derived from a specified taxing entry.
- Entry 50 of List II is subordinated only to the extent of any limitations that may be imposed by Parliament by law relating to mineral development. Unless Parliament imposes a limitation, the plenary power of the state legislature to levy taxes on mineral rights is unaffected.
- The question of an overlap between the taxing entry and general entry does not arise because Parliament cannot impose taxes on minerals under Entry 54 of List I.

Residuary powers of parliament – Entry 97 of List I

- As per the Scheme of Seventh Schedule to the Constitution r/w Article 248, the parliament has powers to legislate on any matter including imposing of taxes when there are no specific entries in List II and List III. Eg. Service tax, Expenditure tax, Gift tax, etc. under Entry 97 of List II (Residuary Entry).
- In para 198 of the majority judgement, it was put forth that if Parliament has no legislative competence to tax mineral rights under Entry 54 of List I, can it make use of its residuary powers in Entry 97 of List I to gain legislative competence? The Hon'ble Supreme Court emphatically negated this proposition. It clearly said the answer has to be in the negative.
- In *International Tourist Corporation vs. State of Haryana* [(1981) 2 SCC 318 [6-A]], the Hon'ble Supreme Court held that it is necessary to establish the legislative incompetence of the State legislature before Parliament can claim exclusive legislative competence by resorting to the residuary power. A matter can be brought under Entry 97 of List I only if it is not enumerated in List II or List III and in the case of a tax if it is not mentioned in List II. Importantly, it

was also observed that the residuary powers of the Union cannot be interpreted so expansively as to whittle down the power of the State legislatures.

- A subject can be brought under Entry 97 of List I only if it is not enumerated in either List II or List III (*All India Federation of Tax Practitioners v. Union of India*, (2007) 7 SCC 527 [46]).
- The enumeration of taxes on mineral rights in List II is a constitutional entrustment to the states. This Hon'ble Court is bound to abide by the constitutional distribution of legislative powers. The distribution also subserves the principles of fiscal federalism.
- The field of tax on mineral rights vests with the state legislature. Parliament cannot impose a tax on mineral rights under Entry 54 of List I. Parliament cannot resort to its residuary powers to tax mineral rights when the subject matter is specifically enumerated in Entry 50 of the State List. The fixation of the rates of royalty under Section 9 can be validly traced to Entry 54 of List I because royalty is not a tax. The fixation of the rates of royalty falls with the regulatory powers of Parliament under Entry 54 of List I.

Entry 49 of List II

- The Hon'ble Supreme Court also turned its attention to the Entry 49 of List II which talks about “TAXES ON LANDS AND BUILDINGS”.
- Taxes on lands and buildings is again under the domain of the State Governments as per the scheme of Seventh Schedule to the Constitution. Definitely this Entry is to the exclusion of all entries in List I to Seventh Schedule that fall in the domain of the Parliament / Central Government.
- The Hon'ble Supreme Court (Constitution Bench) in *Raja Jagannath Baksh Singh v. State of Uttar Pradesh* [(1963) 1 SCR 220] has held that word “lands” is wide enough to include all lands, agricultural or otherwise.
- A tax under Entry 49 of List II is not only levied on the owner of the land, but also an occupier (*Anant Mills Co. Ltd. v. State of Gujarat* (1975) 2 SCC 175). Similarly, a tax on mineral rights could be levied on any person who has an interest in the minerals.
- Therefore, the Hon'ble Supreme Court concluded that lands shall include mineral bearing land as well. Taxes, if any, can be levied only by the State Government/s and not by the Central Government (Para 325 of the majority judgement refers).
- Para 327 of the majority judgement - the Hon'ble Supreme Court came to the conclusion that royalty is not a tax but a statutory consideration payable by the lessee to the lessor for the exercise of mineral rights and hence is forming part of MMDR Act, 1957 in section 9 of the Act.
- In a challenge before the Hon'ble Supreme Court in

Goodricke Group Ltd v. State of West Bengal (1995 Supp (1) SCC 707[20]) – 3 Judge Bench, the primary issue before the Hon'ble Court was whether the impugned levy (rural employment cess @ twelve paise for each kilogram of green tea leaves produced at the estate) was a levy on lands within the meaning of Entry 49 of List II of the Seventh Schedule. Justice B P Jeevan Reddy, speaking for the three-Judge Bench, observed that the income or yield of a land or building can be taken as a measure of the tax on land and buildings. Hence, the measure of the tax based on the yield from the land was held to be valid.

- Parliament had enacted the Tea Act in pursuance of Entry 52 of List I of the Seventh Schedule. Section 25 imposes a duty of excise on all tea produced in India @ not exceeding fifty paise per kilogram as the Central Government may notify. The issue was whether the levy under Section 25 (which is measured on the basis of the quantum of tea produced) denuded the State legislature of the competence to impose a cess on land adopting the same measure (para 309 of majority ruling refers).

- The Hon'ble Supreme Court in para 310 of majority judgement, observed that both the levies are different – while excise duty is on the produce of the land, land cess is a tax on land. Section 25 of the Tea Act enacted by Parliament was held not to deprive the State legislature of its power to levy a tax on lands comprised in a tea estate. The declaration in Section 2 of the Tea Act was held not to affect the legislative competence of the State legislature to levy land cess since it did not seek to control the cultivation of tea but sought to tax tea estates. The land cess was construed not to be on the tea industry, but a cess on land comprised in tea estates.

- After the decision in *Goodricke* (supra) in particular, it is now well established that the income or yield of land can be adopted as a measure of tax.

- Para 330 of the majority judgement, the Hon'ble Supreme Court held that royalty can be considered as an income if it is paid to a private landowner. In case the minerals are vested in the State, the royalty is paid to the State Government, and hence assumes the form of non-tax revenues.

Using same measure in Entries 50 & 49 of List II

- The Hon'ble Supreme Court in para 339 of the majority judgement considered that both the entries 49 and 50 of List II deal with distinct subject matters. Both the entries operate in different fields without any overlap. The fact that mineral value or mineral produced is used as a measure under Entry 50 of List II does not preclude the legislature from using the same measure for taxing mineral bearing land under Entry 49 of List II.

- Para 341 of the majority judgement, the Hon'ble Supreme Court - The words “lands” under Entry 49 of List II

includes mineral bearing land. The mineral produce is the yield from a mineral bearing land. Since royalty is determined on the basis of the mineral produce, royalty can also be used as a measure to determine the tax on royalty. The fact that the State legislature uses mineral produce or royalty as a measure does not overlap with Entry 50 of List II.

Conclusions in the judgement dated July 25, 2024

- Royalty is not a tax. Royalty is a contractual consideration paid by the mining lessee to the lessor for enjoyment of mineral rights. The liability to pay royalty arises out of the contractual conditions of the mining lease. The payments made to the Government cannot be deemed to be a tax merely because the statute provides for their recovery as arrears

- Entry 50 of List II does not constitute an exception to the position of law laid down in *M P V Sundararamier* (supra). The legislative power to tax mineral rights vests with the State legislatures. Parliament does not have legislative competence to tax mineral rights under Entry 54 of List I, it being a general entry. Since the power to tax mineral rights is enumerated in Entry 50 of List II, Parliament cannot use its residuary powers with respect to that subject-matter;

- Entry 50 of List II envisages that Parliament can impose “any limitations” on the legislative field created by that entry under a law relating to mineral development. The MMDR Act as it stands has not imposed any limitations as envisaged in Entry 50 of List II;

- The scope of the expression “any limitations” under Entry 50 of List II is wide enough to include the imposition of restrictions, conditions, principles, as well as a prohibition

- The State legislatures have legislative competence under Article 246 read with Entry 49 of List II to tax lands which comprise of mines and quarries. Mineral bearing land falls within the description of “lands” under Entry 49 of List II

- The yield of mineral bearing land, in terms of the quantity of mineral produced or the royalty, can be used as a measure to tax the land under Entry 49 of List II. The decision in *Goodricke* (supra) is clarified to this extent;

- Entries 49 and 50 of List II deal with distinct subject matters and operate in different fields. Mineral value or mineral produce can be used as a measure to impose a tax on lands under Entry 49 of List II.

- The “limitations” imposed by Parliament in a law relating to mineral development with respect to Entry 50 of List II do not operate on Entry 49 of List II because there is no specific stipulation under the Constitution to that effect; and

- The decisions in *India Cement* (supra), *Orissa Cement* (supra), *Federation of Mining Associations of Rajasthan*

(supra), Mahalaxmi Fabric Mills (supra), Saurashtra Cement (supra), Mahanadi Coalfields (supra), and P Kannadasan (supra) are overruled to the extent of the observations made in the present case.

Conclusions in the judgement dated August 14, 2024

- The submission that judgement dated July 25, 2024 (supra) should be given prospective effect is rejected.
- The States may levy or renew demands of tax, if any, pertaining to Entries 49 and 50 of List II of the Seventh Schedule in terms of the law laid down in the decision in MADA Judgement dated July 25, 2024 (supra) the demand of tax shall not operate on transactions made prior to 1 April 2005;
- The time for payment of the demand of tax shall be staggered in instalments over a period of twelve years commencing from April 1, 2026; and
- The levy of interest and penalty on demands made for the period before 25 July 2024 shall stand waived for all the assesses.

PART B : IMPACT OF HON'BLE SUPREME JUDGEMENT ON THE MINING INDUSTRY

For a change the Central Government and the Respondents or Mining Lease holders or Miners were on one side and the State Government/s were on the opposite side demanding powers to levy cess or other taxes on minerals or mineral bearing lands and the Hon'ble Supreme Court by considering the powers bestowed on the State Government/s under List II of Seventh Schedule to the Constitution has upheld the powers to levy cess or other taxes on grant of mineral rights and also on the mineral bearing lands and using royalty or quantum of minerals excavated as a measure to levy cess or other taxes under Entries 49 & 50 of List II.

In addendum, land is always a state subject (Entry 18 of List I) and the mineral bearing states have started exercising powers under Entries 49 and 50 of List II to Seventh Schedule of the Constitution and have come up enactments to levy cess or other taxes on mineral rights or mineral bearing lands in their state jurisdiction.

Certain state enactments (on illustrative basis) are mentioned as here-below:

I. State of Jharkhand has promulgated Jharkhand Mineral-Bearing Land Cess Act 2024 (Gazette Notification No. 625, dated 07.10.2024) and is levying cess on mineral bearing land as under:

Sl. No.	Classification of Mineral Bearing land	Rate of Cess (per metric tonne of mineral dispatch) upto 18.03.2025	Rate of Cess (per metric tonne of mineral dispatch) w.e.f. 19.03.2025
1	Coal bearing land	Rs. 100	Rs. 250
2	Iron ore bearing land	Rs. 100	Rs. 400

3	Bauxite bearing land	Rs. 70	Non metallurgical grade – Rs. 116 Metallurgical grade – 0.30% of LME (Aluminium) price
4	Limestone bearing land	Rs. 50	Rs. 40
5	Manganese ore bearing land	Rs. 50	Refer Notification No. 01/2024-812, dated 19.03.2025.
6	Any other mineral bearing land	50% of royalty paid	

II. State of Tamil Nadu has promulgated the Tamil Nadu Mineral Bearing Land Tax Act, 2024 vide Tamil Nadu Government Gazette Extraordinary No. 79, dated 20.02.2025 and is wanting to levy mineral bearing land tax on the land bearing any mineral as under:

Sl. No.	Name of the Mineral	Rate of tax per metric tonne	Rate of tax per cubic meter
1	Lignite	Rs. 250	---
2	Limestone	Rs. 160	---
3	Rough stone	Rs. 90	Rs. 140
4	Black Granite.	Rs. 420	Rs. 1,300
5	Other minerals	Refer TN Govt. Gazette Extraordinary No. 79, dated 20.02.2025	

Date of implementation - The Govt. of Tamil Nadu has implemented the above taxes w.e.f. April 4, 2025.

III. State of Karnataka has recently considered and passed the Karnataka (Mineral Rights and Mineral Bearing Land) Tax Bill, 2024 and is proposing to levy cess on mineral bearing lands along with mineral rights tax as under:

Rates on tax on mineral bearing land (illustrative basis)

Sl. No.	Mineral	Tax – Mineral bearing land
1	Iron-ore (CLO, Lumps, Fines and concentrates of all grades)	Rs. 100 per tonne
2	Limestone (i) L.D. Grade (less than 1.5 percent silica content) (ii) Others	Rs. 25 per tonne Rs. 20 per tonne
3	Manganese Ore (i) Ore of all grade (ii) Concentrates	Rs. 100 per tonne Rs. 100 per tonne
4	Chromite	Rs. 100 per tonne
5	Copper ore	Rs. 50 per tonne
	Other notified minerals	Please refer to the proposed Bill.

Part A – Rates of tax on mineral right in respect of leases granted through non-auction

Sl. No.	Mineral	Mineral Right Tax
1	Iron-ore (CLO, Lumps, Fines and concentrates of all grades)	Equivalent to three times Royalty payable
2	Limestone (i) L.D. Grade (less than 1.5 percent silica content) (ii) Others	Equivalent to 1.25 times Royalty payable
3	Manganese Ore (i) Ore of all grade (ii) Concentrates	Equivalent to 1.25 times Royalty payable
4	Chromite	Equivalent to three times Royalty Payable
5	Copper ore	Equivalent to Royalty Payable
	Other notified minerals	Please refer to the proposed Bill.

In case of Part E – Rates of tax on mineral right in respect of leases granted through auction : The State of Karnataka is proposing to levy Rupee one per metric tonne.

The aforesaid bill is passed by the legislative assembly and is sent to the Hon'ble Governor of Karnataka, who in turn has forwarded the same to the Hon'ble President of India for consideration.

Many more states shall definitely follow the examples of Jharkhand, Tamil Nadu and Karnataka in implementing laws in connection with levy of cess and other taxes on mineral bearing lands and mineral rights tax.

As can be seen above, the rate of cess and mineral right tax are not uniform and varies from state to state. In addendum, with the change in dispensation every five (5) years or less the rates shall drastically undergo a change and definitely shall be on an upward trajectory and this shall make the prices of essential minerals to go up and price differences between states shall be substantial purely on account of state levies viz., cess or other taxes on mineral bearing land and on mineral rights.

The mining lease holders have to mandatorily pay auction premium (where applicable), royalty, Contributions to DMF & NMET and the cess & other taxes levied by the respective State Government. In addendum even GST will have to be paid on all of them.

PART C : WAY FORWARD POST THE HON'BLE SUPREME JUDGEMENT

The judgement/s of the Hon'ble Supreme Court is the law of the land and in a democratic set-up no Government can gloss over the impact of the judgement rendered by the Hon'ble Supreme Court. No one Government at the State

or Central level can nullify the impact of the judgement of the Hon'ble Supreme Court by amending any piece of legislation, since the bifurcation of powers are very clearly laid out and this judgement in crystal clear terms has identified who has the powers to regulate and to levy fees / consideration or taxes on grant of mineral rights or on mineral bearing lands.

If at all, the polity chooses to bring in amendments to the extant MMDR Act, 1957 then it calls for no less than a constitutional amendment requiring two-thirds majority in both the houses of Parliament along with ratification by at-least fifty percent of States in the country and definitely no states would want to let go of this opportunity to exercise powers under Entries 49 & 50 of List II to the Seventh Schedule of the Constitution.

Immediately, the Central Govt. can put in restrictions or prohibition on the states power to levy taxes on mineral rights given to the State Government/s under Entry 50 of List II, but is powerless in reigning the State Government/s owing to Entry 49 of List II. If the Central Government aims to curtail or prohibit powers of the State Government/s under Entry 50 of List II, then the State Government shall ignore Entry 50 of List II and shall exercise powers granted to them under Entry 49 of List II.

In the humble opinion of the writer, the Central Government should take a cue from the way the Goods and Services Tax (GST) is introduced in the country by bringing an amendment to the Constitution (101st Constitution Amendment Act, 2016) and has merged various indirect taxes viz., VAT, Luxury tax, Entertainment tax, Entry tax etc. levied by states in different states with different rates of taxes on commodities / goods and taxes on services being levied only by the Central Govt. and truly it has now become one nation one tax for a particular commodity or goods w.e.f. July 1, 2017 and is successfully managed through GST Council owing to introduction of Article 279A by heavily relying on the concept of Co-operative federalism and every decision of rate hikes or rate reduction in GST across the country is put up and debated in the GST Council meetings comprising representatives of all State Governments with the Central Government's Hon'ble Finance Minister as the Chairperson and the voting rights being distributed in the ratio of 1/3 : 2/3 between Central Government and State Government/s and any matter needs to be decided with 3/4th majority if not unanimously.

For example – Iron-ore is taxed i.e. GST levied uniformly @ 18% across the states, irrespective of where the lease is situated. If at all a particular state wants to increase / decrease the rates of GST, then it shall be put up and debated in the GST Council and if all the members agree then the proposal shall be recommended to the Central Govt. for notification in the Gazette along with notifying the date of implementation. Once the Central Govt. notifies

then all the State Government/s shall simultaneously issue Gazette Notification on the same lines as the Central Government has done.

The system is working fine with the involvement of GST Council for the last about 8 years and the states have also seen increase in tax revenues after introduction of GST.

On the same lines as GST Council, the Central Government should amend the Constitution and identify mineral bearing states and bring in a concept of Mineral Bearing Land / Mineral Rights Tax Council and get the states to agree on the same so that the disparities in levy of Cess or other taxes on grant of mineral rights or on mineral bearing land is

removed and the trade / business entities having mining leases are aware of taxes / levies irrespective of the states / regions in which they operate. Else it shall be very destructive to the industry and shall also lead to arbitrage owing to operations being carried out in states where lower cess or other taxes are applicable when compared to states where cess or other taxes are relatively on the higher side.

This is the need of the hour and as it stands today. There is no way the Central Government can control or restrict or prohibit States from charging cess or other taxes under Entries 49 or 50 of List II to the Seventh Schedule without bringing in amendments to the Constitution.

PS. - The views expressed hereinabove is personal and is that of the author / writer only. It is not made on behalf of Mining Engineers' Association of India (MEAI) or on behalf of the Institute of Chartered Accountants of India (ICAI).



CALL IT MINERAL LAND

Dr Meda Venkataiah,
Director,
M/s. MSPL Limited, RMML & AISL
Hosapete, 583203,
Vijayanagar, Karnataka
meda.venkataiah@baldota.co.in

ABSTRACT

India's ambition for industrial growth and infrastructure development is heavily reliant on the mining sector, which provides vital raw materials. However, a significant barrier exists in the form of mineral-bearing areas classified as forest land — a legacy of the 1865 Forest Act. These classifications, made without accounting for subsurface mineral wealth, now delay mining clearances and threaten national production goals. This paper advocates for a new classification — “Mineral Land” — for mineral-rich zones to facilitate timely and sustainable mining activities. With adequate environmental safeguards and regulatory oversight in place, reclassifying such areas can ensure a balance between ecological protection and economic advancement.

INTRODUCTION

The designation of Forest Land in India began with the Forest Act of 1865, which aimed to protect natural vegetation and ecological balance. However, this classification did not consider the geological fact that many mineral deposits predate the forests and were unknowingly included in protected zones.

Mining, alongside agriculture, is among the oldest human activities and remains the backbone of modern economies. From everyday items to high-end technology, minerals are fundamental. With India's growing population and industrialization plans, mining is not a choice but a necessity.

Despite policy reforms promoting ease of doing business, delays in obtaining forest clearances — often taking 3 to 4 years — undermine the country's ability to meet strategic goals, such as those outlined in the National Steel Policy (NSP). It is, therefore, imperative to differentiate mineral-bearing regions from general forest land and facilitate access for sustainable mining.

ADVANTAGES OF DECLARING MINERAL-BEARING AREAS AS “MINERAL LAND”

1. Expedited Clearances:

Dispensing with the prolonged forest clearance process can significantly reduce project lead time, enabling faster development and production.

2. Alignment with National Goals:

Helps meet the National Steel Policy (NSP) targets by ensuring timely availability of essential raw materials like iron ore.

3. Sustainable Regulation:

Mining operations are already monitored by robust regulatory bodies such as the Indian Bureau of Mines (IBM) and Directorate General of Mines Safety (DGMS), ensuring safety and environmental compliance.

4. Insignificant Land Use Impact:

Mining currently occupies only 0.02% of India's geographical area and 0.832% of forest land — an extremely small footprint that does not compromise overall forest cover targets.

5. Economic Upliftment:

Recognizing mineral lands can boost employment, local infrastructure, and revenue generation, especially in mineral-rich rural regions.

6. International Competitiveness:

Fast-tracking mining projects can help India compete with countries like China, which has embraced mining as a foundation for industrial and economic strength.

RECOMMENDATIONS

1. Policy Reclassification of Mineral-Rich Forest Areas:

Formulate a national framework to identify and reclassify mineral-bearing zones within forest areas as “Mineral Land” with conditional safeguards.

2. Single-Window Clearance System:

Establish a centralized portal under MoM (Ministry of Mines) for fast-tracking clearances by integrating IBM, MoEFCC, DGMS and State authorities.

3. Land Zoning and Mapping:

Use satellite imaging, GSI (Geological Survey of India) data, and mineral exploration reports to predefine Mineral Land zones.

4. Public-Private Consultation Mechanism:

Regular dialogues between mining companies, local communities, and environmentalists to ensure transparency and mutual benefit.

5. Environmental Safeguards & Rehabilitation Plans:

Mandatory mine closure and post-mining restoration plans to ensure environmental protection while allowing mineral extraction.

CONCLUSION

Minerals are nature's gift, embedded in the earth long before legislative boundaries like forest land were drawn. In a rapidly developing nation like India, it is time to rethink outdated classifications that obstruct progress. Declaring mineral-bearing areas as "Mineral Land" is not only a rational step but a necessary one — balancing economic development with environmental stewardship. With strong regulatory mechanisms already in place, this shift can unlock the true potential of India's mineral resources and accelerate the journey toward self-reliance and global leadership in industrial growth.

Yes — It is Mineral Land, not Forest Land. Let us work for this.



Drone Adoption in Indian Mining: Regulatory Trends and Global Opportunities

Sanjeevani Jawadand-1*, Ashwini Danao-1, Pratik Godbole-2, Kirtikumar Randive-2

1-Shri Mathuradas Mohota College of Science, Nagpur

2-Post Graduate Department of Geology, RTM Nagpur University, Nagpur

Correspondence*: ketki06012013@gmail.com

Abstract

The mining industry in India will be crucial for attaining the goal of Viksit Bharat 2047. Our nation has the ability to lead sustainable and innovative mining with its enormous mineral resources. In the dawn of technological advancement, the revolutionary technologies like drones, AI and blockchain technology have unseen growth prospects in mining industry. The popularity of unmanned aerial vehicle (UAV) in exploration, surveying and mapping to ensure safety and security is immensely grown in recent years. It has the ability to transform the Indian mining sector offering operational efficiency and ensure safety in difficult terrain like mine pits, tailing dams, and stockpiles. In order to ensure this transformation, we need to create clear, flexible, and consistent rules and regulations. While establishing rules and regulations for the use of drone technology, stakeholder participation, following international standards, and ways to encourage innovation while keeping safety and the environment in mind are all very important. This research review presents India's current rules and regulatory framework, challenges and global opportunities considering drone technology.

Introduction

Mining is crucial to India's economy, contributing to economic growth and infrastructural development. India has significant natural resources, including coal, iron ore, bauxite, limestone, and industrial minerals. These resources are crucial for the nation's industrial and energy needs. The mining industry contributes significantly to India's GDP, mostly via mineral and metal production, and supports other sectors such as construction, manufacturing, and energy. By adopting cutting-edge technologies, the mining industry is undergoing a substantial transformation which improves sustainability, safety, and productivity. Among these technologies, drones, or Unmanned Aerial Vehicles (UAVs) have emerged as potent tools (Mohsan et al., 2022). These are capable of executing a variety of tasks with unprecedented precision and efficiency. Their capacity to produce precise 3D models, get high-resolution aerial photos, and access difficult-to-reach locations has made them indispensable, especially in

locations that are often dangerous or inaccessible using traditional methods (Quamar et al., 2023).

Mining activities, which are often located in distant and difficult-to-access areas, may make human accessibility challenging. This, in turn, causes either decision-making delays or a lack of appropriate information, resulting in a loss of mining efficiency and a hazard to worker safety. The rise of the drone industry in India began with the government's introduction of liberalised drone regulation in August 2021, which was expected to propel India into 'an era of supernormal growth.' Crewed aerial surveys and satellite imaging are useful traditional methods, but they may be limited by high prices, logistical problems, and safety concerns. Drones are a cheap way to quickly get high-quality data. But the ambiguity in rules for mining applications make it difficult for a lot of people to use it (DGCA, 2021). So, there is a need of comprehensive, flexible, and integrated policies like Australia's automated airspace management, the European Union's strict legal standards, and Canada's integrated regulatory frameworks (Dolata and Schwabe, 2023). India may be able to use these concepts to prepare a robust, clear regulatory environment that encourages innovations in certain sectors. This study analyses India's current regulatory environment, highlights major improvements and problems, consider new policy ideas to prepare an integrated framework that follows international standards. This will ultimately help the policymakers, industry players, and regulatory agencies utilize drone technology responsibly in mining and other industries by focusing on stakeholder inclusion, technological advancement, and environmental safeguards.

Drone survey in Indian mining

Drone technology can be extensively applied in the mining sector, such as carrying out overall surveys of mines, demarcating lease boundaries using Ground Control Points (GCPs), monitoring illegal mining activities, volumetric estimation of excavation, reclamation, and periodical stock piles monitoring, change detection analysis over time using previously surveyed data, monitoring land use and environmental impact in and around mining areas, virtual

inspection of mines for regulatory purposes, and preparing contour surveys and survey maps for filing to various regulatory agencies and internal use of the industry.

A base line and periodic drone survey data will be used for scientific evaluation of mineral amount in order to deter unlawful mining in quarries. This will be accomplished via the use of drone survey. The purpose of drone surveys is to ensure the safety and efficiency of lease management for minor mineral quarries. Drones have the ability to visit potentially dangerous places without putting human surveyors in danger. In comparison to more conventional approaches, drone surveys are able to cover vast regions in a short amount of time, which significantly cuts down on the amount of time needed for data collecting. Through the prevention of illicit mining, it is possible to guarantee that mining operations are carried out in accordance with the rules. The use of such technical advancements would result in higher levels of transparency and organization within the operations. Mining firms are able to receive vital information in a short amount of time through rapid data gathering, which enables them to make decisions and modifications to their operations in a timely manner. The use of drones that are fitted with sophisticated sensors allows for the acquisition of high-resolution photos as well as precise topographic data, which ultimately results in 3D models of mining sites that are more accurate and detailed. For example, projects such as the Kerala Mineral Drone LiDAR Survey (KMDL) (Ministry of mines, 2025). Utilizing cutting-edge unmanned aerial vehicle (UAV) technology, Drone Survey and Volumetric Analysis are able to collect high-resolution aerial data, which allows for accurate mapping and measuring of mining areas. This method makes it possible to accurately calculate the quantity of materials that are extracted, enhances the efficiency of operations, and contributes to improved resource distribution.

Current Regulatory Framework in India

The Drone Rules I were published by the Ministry of Civil Aviation in gazette notification CG-DL-E-26082021-229221 on August 25, 2021. The documentation for Unmanned Aircraft Systems was published in government notification CG-DL-E26012022-232917 on January 26, 2022 (Kaushal, 2022). Indian Bureau of Mines issued Standard Operating Procedures (SOPs) under sub rule (5) of rule 34A of MCDR, 2017 for drone surveys and digital aerial images of mining areas, emphasizing registration, pilot certification, airspace regulations, and drone specifications. In 2021, the Indian Ministry of Mines revised the Mineral Conservation and Development Rules (MCDR), 2017 to compel lessees and preferred bidders to provide digital pictures to the IBM. Rule 34A of MCDR requires lessees with an annual excavation plan of one million tons or more or leased areas of fifty hectares or more to conduct a drone survey of their leased area and up to 100 meters beyond the lease border in April or May. The Controller General, Indian

Bureau of Mines, must receive processed output, including DEM and Orthomosaic pictures, by July 1. Drone agency registration and permissions are not required for drone surveys in mining areas. If any law restricts the use of drones, the IBM may prescribe an alternate mechanism for survey and data or image submission. Drone companies doing mine assessments must follow DGCA laws, regulations, and recommendations. The DGCA must approve and mandate safety elements for mining lease drone surveys. A 20 mega pixel or higher RGB camera with a GSD of less than 5 cm per pixel should be utilized. DEM resolution should be 15 cm per pixel or above. The drone flight route and height should be designed to generate a photogrammetric height model. The drone's flying height should be DGCA-approved, yet its imaging resolution should be good. Camera nadir should be vertically downward (90°).

Policy reforms

Though the drone rules and procedures have defined for drone surveys in mining, we need robust, adaptable regulatory frameworks that balance safety, privacy, innovation, and environmental preservation. Policymaking is more credible and effective when all the stakeholders including regulators, businesses, local communities, and environmental organizations participate in the policy-making process. ICAO's UAS Roadmap and the European Union's EASA rules are the examples of how coherent standards may help technology work together and be more compatible (ICAO, 2019; EASA, 2020, 2025). Also, with the advancement, remote identification, geofencing, BVLOS operations, and autonomous flying are becoming more and more important. Technology changes quickly, therefore regulations must be adaptable and practical and should be in accordance with international standards to support resource-intensive industries like mining (EASA, 2025).



Fig. I Policy innovations

Policy reforms aim to simplify drone operations and grow the sector. Enterprises, research organisations, and government agencies employing drones may self-certify via the Digital Sky Platform, reducing registration and approval periods (GreyB Services, 2025). The government has pilot programs and regulatory testing zones in mining to study autonomous and BVLOS drone operations. India is adopting Australian and European airspace control methods like automated air traffic management to facilitate large-scale

drone use in mining and other industries. Environmental safety has improved by geofencing critical areas and real-time drone environmental impact studies. Under "Make in India," the government promotes indigenous manufacture and innovation, including drone technology for India's difficult terrain. And the operators and regulators are being trained and accredited to ensure safe, compliant, and effective mining drone use.

Challenges in Drone Adoption and Regulation

Numerous individuals are endeavouring to increase the use of drones in the mining sector of India; however, several issues need to be resolved before its widespread implementation. The issue of effective management of airspace arises due to the scarcity of automated systems for disaster prevention and real-time traffic management. These are crucial for the autonomous and long-distance operations of large mining initiatives. Also, the absence of a comprehensive remote identification system has an impact on safety and security. Moreover, excessive number of rules and regulations, which hinders the collaboration between the DGCA and state or municipal agencies cause the problem. This complicates the process of adhering to the regulations and increases the cost of compliance. These issues may be resolved through the implementation of industry-specific set of regulations. The steady internet, GPS signals, and communication infrastructure that autonomous drones require to function are not present in various remote mining locations, which complicates the process of scaling up. Additionally, there are concerns regarding privacy and the law, as the collection of high-resolution data raises questions regarding its security and privacy. In order to provide assurance about unambiguous safeguards, legislation continues to evolve. Staffing issues are also a significant obstacle. The insufficient number of competent personnel who are capable of operating drones, adhering to regulations, and managing incidents renders it difficult to maintain oversight. Also, the issue of obtaining community acceptance remains a challenge, particularly in protected regions and indigenous territories. In these areas, concerns regarding the environmental impact and social acceptability necessitate a combination of flexible legislation and meticulous planning.

Future Policy Recommendations

Optimizing drone technology in India's mining industry requires vigilance and collaboration. An effective structure will be formed with mining-specific legislation that addresses safety, environmental, and land rights and aligns with ICAO and ISO standards. A centralized digital system that combines real-time BVLOS flight approvals, remote identification, and geofencing with existing air traffic control systems has to be added to Digital Sky to improve operations. GIS-based geo-fencing will provide insight into no-fly zones surrounding airports, military regions, protected lands, and mining sites, according to the

European Commission (2020). Critical or rare tasks demand some flexibility. The DGCA can establish appropriate and adaptive regulations by creating specialized regulatory staff and platforms with industry, community, and environmental stakeholders. Advanced technologies like automated air traffic management and infrastructural improvements, especially in distant places, are crucial. Certification of drone operators, regulators, and maintenance workers increases safety and compliance. Innovation will result from autonomous aircraft, AI-based monitoring, and environmental sensing pilot zones and sandboxes in mining operations. Policies have to regulate effect studies, public consultations, noise, and ecological restrictions to protect the environment and community. These policies' global alignment will boost cross-border cooperation, exports, and collaboration with global drone-powered mining enterprises (ICAO, 2019).

Strategy for implementation of stable policy framework

A systematic approach is needed to create a robust mining regulatory framework in India. Regulators, industry leaders, local communities, environmental groups, and security authorities should be involved early and often for regular follow-up. This builds confidence and ensures policies are relevant and openly allied with stakeholder demands. A thorough assessment of existing standards versus international frameworks like Australia's ASM and Europe's EASA is needed to identify shortcomings and mining-specific needs. Set clear objectives and principles that prioritize safety, environmental sustainability, innovation, socio-economic advantages, openness, and adaptability. Mining licensing, operating, and safety regulations are needed. These rules should accommodate new technologies like BVLOS and AI-driven autonomous systems. Pilot projects may test these rules in real-world settings to improve processes and create best practices. After finalization, enforcement authorities with appropriate capability should monitor compliance and use data and stakeholder input to update regulations when new technologies emerge. The DGCA, Ministry of Environment, Forest, and Climate Change, state authorities, mining firms, drone manufacturers, research institutes, local communities, and international standards groups are key players.

Drone Regulation Framework for India's Mining Sector

The regulation of drones in the mining sector of India should be comprehensive and address a variety of issues. Initiating a precise definition of operating categories, including Nano, Micro, Small, Medium, and Large drones. Subsequently, establish license processes for the mining applications associated with each category. Registration, permit issuance, and continuous monitoring for advanced activities such as BVLOS and night flights can be streamlined by a

unified digital gateway that utilizes the Digital Sky platform. In order to safeguard sensitive sites and local residents, geofencing must be implemented to establish no-fly zones, height limits, visual line-of-sight requirements, and operating durations. Impact resistance, obstacle avoidance, and environmental impact evaluations are all mandatory for drones to comply with international safety and environmental standards during all operations. In order to incorporate BVLOS missions into the current airspace, regulations must allow for remote identification and geofencing, as well as collaboration with air traffic authorities to regulate drone traffic. The institutional structures of the DGCA will be enhanced by the establishment of stakeholder-driven rule modification committees, incident investigation, and monitoring. The establishment of regulatory sandboxes would foster innovation, facilitate the testing of new applications, and ensure the ongoing learning and adaptation to international standards.

Conclusion

India is optimistic in drone technology to improve mining. Recently implemented legislative amendments and pilot programs show legislative intent, but airspace management, regulatory uniformity, infrastructure challenges, and community acceptability need to be addressed. Facilitating drone integration improves safety, efficiency, and sustainability. This will be achieved by utilizing global best practices and promoting regulations that are inclusive and adaptable within the industry. By improving its skills, fostering innovation, and harmonizing sector-specific rules, India can lead the ethical use of drones for resource research and management, achieving its smart and sustainable economy aim.

Limitations and Future Research

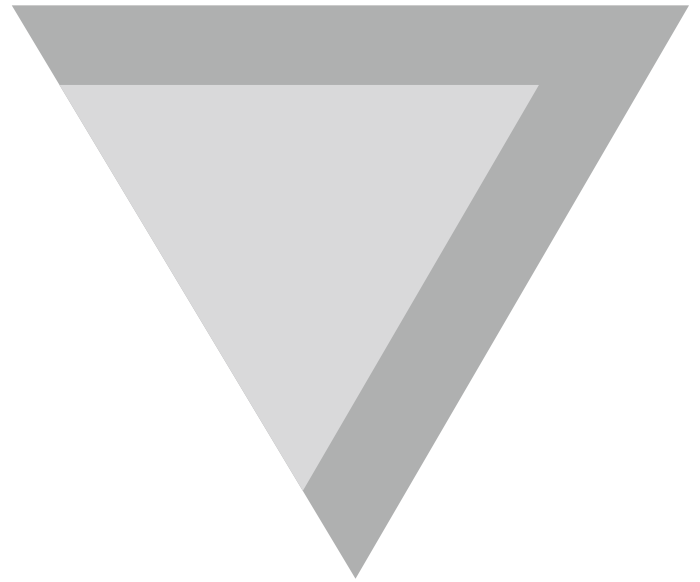
Implementing this paper's policies and global models requires pilot projects, cross-sectoral research, and longitudinal impact evaluations. Future drone integration research should concentrate on regulatory framework operationalization, stakeholder acceptability, distant technology viability, and environmental and social effect evaluations to satisfy sustainability objectives and local community interests.

Future studies should explore the economic impacts of extensive mining drone deployment, including job creation, skill development, and labor dynamics. Drone use in mining areas has long-term environmental effects on animals and ecosystems, therefore adaptive management strategies are required.

Since drone technology is advancing swiftly, cybersecurity, data privacy, and misuse problems must be studied. This complex interlinked challenge requires collaboration between policymakers, technologists, environmental scientists, and social scientists.

References

- DGCA. (2021). Drone Rules, 2021. Directorate General of Civil Aviation, Government of India.
- Dolata M. and Schwabe, G. (2023) Moving beyond privacy and airspace safety: Guidelines for just drones in policing. *Government Information Quarterly* Volume 40, Issue 4.
- EASA. (2020). Easy Access Rules for Unmanned Aircraft Systems. European Union Aviation Safety Agency.
- EASA. (2025). Drones - regulatory framework background. European Union Aviation Safety Agency. <https://www.easa.europa.eu/en/domains/civil-drones/drones-regulatory-framework-background>
- European Commission. (2020). Unmanned aircraft systems in European airspace. *Official Journal of the European Union*.
- GreyB Services (2025) Impact on the Drone industry with the new rules in India. <https://www.greyb.com/blog/drone-industry-in-india/>
- ICAO. (2019). Unmanned Aircraft Systems Traffic Management (UTM) – A Common Framework with Core Principles for Global Harmonization. International Civil Aviation Organization.
- Kaushal, Hitanshu & Bhatnagar, Anupam. (2022). APPLICATION OF DRONES IN MINING INDUSTRY - RULES, GUIDELINES AND CASE STUDY. 9. d459.
- Ministry of mines (2025) Report on States' Best Practices in Mining. Federation of Indian Mineral Industries (FIMI), New Delhi. <https://mines.gov.in/admin/download/685a874e549cd1750763342.pdf>
- Mohsan, S. A. H., Khan, M. A., Noor, F., Ullah, I. & Alsharif, M. H. Towards the unmanned aerial vehicles (UAVs): A comprehensive review. *Drones* 6(6), 147 (2022).
- Quamar, M. M., Al-Ramadan, B., Khan, K., Shafiullah, M., & El Ferik, S. (2023). Advancements and Applications of Drone-Integrated Geographic Information System Technology—A Review. *Remote Sensing*, 15(20), 5039. <https://doi.org/10.3390/rs15205039>



Underground Mining





Stoping Methods for Thick and Wide Orebody

M. N. Bagde, A. G. Sangode & A. K. Raina

CSIR-Central Institute of Mining and Fuel Research, Nagpur Research Centre,
17/C, Telangkhedi, Civil Lines, Nagpur, India 440 001

email: mnbagde.cimfr@csir.res.in

Abstract

The wide and thick ore body at one of the metal mines from the central India was associated with the complex geology and rock structure and was a challenge to extract it. Rock mechanics studies along-with various empirical and numerical approaches in vogue were applied to arrive at the safe stoping parameters along-with the support system requirement. Keeping in view, present infrastructure available and the availability of the trained manpower at the mine, Room-and-Pillar with post-pillar as a possible method of stoping was planned. Also, multi-lift sublevel cut and fill mining and CUDF mining is discussed as a possible futuristic high recovery mechanised mining methods for the given geo-mining and the rock mass conditions. The present paper presents the results obtained from the various studies including hydro-geological, rock mechanics and rock mass characterization as well as numerical modelling to arrive at the stoping method planned for its extraction.

Introduction

MOIL is the country's highest producer of high-grade manganese ore. At present, it fulfils 80% of the country's need of the high-grade manganese ore which is an important constituent for the steel making. In-early 1896, the establishment of the central provinces prospective syndicate, started its first mine within central India very near to the Nagpur. The mine was first started its operation by opencast working and after reaching its economic limit underground method of working was adopted by driving an incline during the seventies. During eighties deeper underground levels were opened up by putting vertical shaft. At present underground working is spread over in four and more levels at this mine. Total strike length of deposit is approximately at 600 m, which has been differentiated as North Limb, South Limb, South Limb extremity. The wide thick ore body encountered in the South extremity was of great importance due to its ore quality. At same time, method for its recovery was also challenge, since, this ore body is associated with the complex rock-mass and geological structure. The present paper discusses in detailed the rock mechanics and numerical modelling studies carried out and feasibility of the

few suitable methods to recover this type of thick and wide orebody.

Orebody

The S-shaped ore body is divided into 3 sections: the North Limb, the South limb and the South limb extension with extremity. The study in this paper covers south limb extremity with the 60-90 m wide ore body and 15 to 20 m thick dips at 20-30 degrees. The deepest level is at approximately 185 m below the surface. While, in the south limb extension the 25-30 m wide ore body dips at 45 to 50 degrees. This means ore body has plunged and the geological disturbances are the main cause towards the complex structure of the ore body. In this zone, the hangwall was highly sheared to a distance of 8-10 m, while shear zones also existed in the footwall at a distance of 3-10 m. The orebody was friable in nature. The orebody was then comprised of banded rhodonite, manganese quartzite, while the hangwall formations was mostly comprised of pink gneiss.

Geo-Hydrological Investigations

In this mine vicinity, it was observed through hydrological studies that immediately below the soil cover/detrital mattle was the presence of consolidated Dolomite Kast formation with primary as well as secondary porosity. The solution channel filled with water was the main water body. The fractured dolomite stone i. e. hard stone along with Kast formation were the source for storage and movement of the ground water. The formation of Kast might be the solution cavity and could be extensive in nature with a uniform spread all over the area. Ground water occurred in the pore spans as well as in the fractures and cracks in a semi-confined state. The thickness of aquifer was found ranging from 20-75 m and average being at 50 m. The yield varied from 2 to 6 lps. The compact consolidated granite gneiss acted as confining bed at places thereby existence for the second dolomite Kast aquifer. The compact gneiss without fracture might be acting as aquifuge and was associated with the ore body. This was neither porous nor permeable. This might not allow water to percolate in to the mine. However, aquifer-aquiclude cross-flow- were associated with aquiclude quartz mica schist between two

dolomite Kast aquifer possess a complex hydrological condition. This was a significant aspect in this context of mining and modelling, an important controlling factor for the ground water inflow into mine. The hydraulic continuity between the Dolomite Kast and quartz mica schist made them a single leaky aquifer. This has established the hydraulic continuity of Dolomite Kast aquifer with ore body, through fractures and joints in the formation system.

It was expected that during the mine development under in-situ condition, the mine inflow most likely would be in-sufficient. In the case during blasting and other mining operations, the fracture, fault and solution channel zones might be activated to encounter the predicted flow per day to the tune of 343, 1087 and 7233 m³/day, respectively. In case all were activated simultaneously, the peak flow would be likely at 8663 with 4235 m³/day as stabilized flow. Thus, the mine should have arrangement for pumping of 10,000 m³/day to meet the sudden in-rush of water and the mine disaster plan should be put in place to meet any risk-based emergencies (Bagde et. al., 2017; Soni et. al., 2017; Bagde, 2014; CIMFR Report, 2012).

Present Method of Mining

Due to typical geological condition in underground, the method of mining practised earlier was flat back cut and fill method with square set system of support and the void so created during the mining operations was to be filled up with waste rock. Presently the same method of mining is continued by replacing conventional square set with cable bolting and rock bolts. The voids created are being filled up with the hydraulic sand stowing compared to the previous support system and filling system, the cable bolting, rock bolting and sand stowing combination was found to be more suitable and has enhanced the productivity as well as helped in achieving the highest level of safety. During the leading mining stripping of 2.8 m height was carried out from the hangwall to footwall and covering the strike length. While carrying out leading mining the back was supported with the rock bolts and followed by the cable bolts.

Geo-technical and Rock Mass Characterization

The uniaxial compressive strength were determined using the Digital Schmidt hammer (Proceq make) rebound number which was found to vary from 38 to 60 MPa. The obtained rebound number from the field study is converted into the compressive strength according to relationship provided in IS code No. 11315 (Part 5) (1987). The quartzite ore materials were relatively weak with average uni-axial compressive strength of 20 to 56 MPa in the case of South extremity ore body.

Bieniawski's (1989) RMR and Barton's Q were used to characterise the rock mass and were used to derive the roof spans and to recommend the support systems. Average combined RMR for various types of rock masses was found

to vary in the range of 30-40, classified as POOR rock mass. According to Barton's Q estimated at 0.04 rock mass was classified as Extremely POOR. Overall rock mass was rated as POOR to Extremely POOR in the South Extremity zone with the impact of the sheared claystone beds and intrusion of quartz mica vein in the ore body and also the presence of surcharged water bearing strata in HW and FW. The rock quality index was much lower in the case of ore body due to being friable in nature, presence of sheared zone and intrusion of quartz and clay bands. Also, Potvin's Stability graph method was used to arrive at safe opening span and support system.

Room and Pillar Stopping Method for Wide Ore Body

Considering total stress at 10.61 MPa and considering Pillar Strength (PS) according to Sheorey's approach, the Safety Factor (SF) was determined at 0.65, which is well comparable with 0.64 in the case of Laubscher's which also considered actual rock mass conditions at the site. From the field observations, it was noticed that due to the vertical and oblique joints sets presence in the ore body, quartz mica schist vein and other geologically weak disturbances and the friable nature of the orebody, occasionally roof failure were reported. To keep intact mine openings and pillars, roof bolts and cable bolts and if needed, wooden chocks and props were also provided which adds to the safety factor. Thus, in the present case considering the support system provided, the Safety Factor was expected to enhance to 1 or more from the calculated one at 0.65 from Sheorey's and Laubscher's approach. Hence, openings were found to be standing without much problem at this mine. However, it shall be noted that opening span be restricted to 2.5 m and primary support in the form of 1.5 m roof bolts followed by 12 m long cable bolts be put in place within the 10 hr of the rock mass exposure. Keeping SF at 1.5 and roadway width and working height both at 2.5 m, the determined average safe square pillar size according to Laubscher's approach is at 22 m. This also matched well with the Coal Mines Regulation (CMR) for the given depth.

Rib and Post Pillar Design

The Tributary area method can provide a conservative estimate of rib pillar stress, if we assume that the panel pillars have all failed or else are all mined-out and therefore carry no overburden stress (Zipf, 2001). The empirical pillar strength formulae mainly apply to pillars with a width-to-height ratio less than 5. For hard rock and other non-coal mines, an equivalent squat pillar formula does not exist. It is necessary to extrapolate Obert-Duvall relation to high w/h ratios or use the Hoek-Brown failure criterion to estimate the required barrier pillar size.

Considering compressive strength at 22 MPa, rib pillar width 6 m, stope height 30 m and depth at 185 m, pillar strength of the rib pillar using Obert-Duvall relationship determined at 18 MPa. Using tributary area method, pillar

load calculated at 10 MPa. Thus, Safety Factor of the 6 m rib pillar determined at 1.8, which is quite enough keeping the long-term safety of the mine workings during the stoping operation. The Hoek-Brown failure criterion can also provide an estimate of the strength for a full-scale cube of the rock mass and determined safety factor is at par that determined with Obert-Duvall.

Thus 6 m width rib pillar with SF at 1.8 was found to be sufficient enough. Also, post pillars be left-out of 5 m thickness for which Safety Factor determined was at 1.5. The present practice being applied at this mine to leave rib pillar at 6 m thickness and post pillars at 5 m thickness found to be appropriate one. The stability of the 6 m rib and 5 m post pillar was also established through the numerical modelling studies using Phase 2D software as shown in Figs. 1 and 2. Two stopes of 20 m thick and 30 m height with 6 m rib pillar in-between these stopes were considered for the numerical modelling studies. In first stage stope 1 was extracted to study stresses and displacements. The extracted stope 1 was then backfilled using sand fill material in stage 2. Followed to this, in stage 3 stope 2 was extracted and its effect on the backfilled column and adjacent rib pillar were studied. It was found that the horizontal displacement (Fig. 1) and horizontal stresses (Fig. 2) developed in the backfilled stope column and in the 6 m rib pillar were at theminimal and found to be stable. Also, it was found that the backfilled material acts as a confinement. Also found to transfer the higher stresses to the abutment or to the surrounding rock mass which is stronger than the backfilled material. From Fig. 2, it was observed that horizontal stresses developed was at the minimal in the backfilled material and thus suggesting standing on its own - the principle mostly backfill works on.

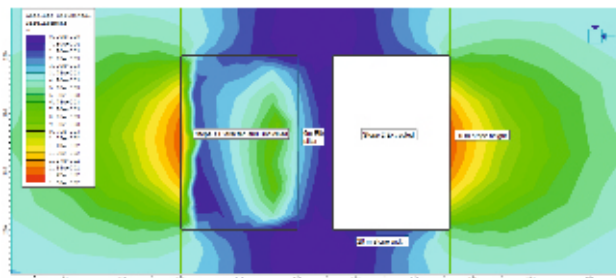


Fig. 1. Horizontal displacement developed in the rib and backfilled column

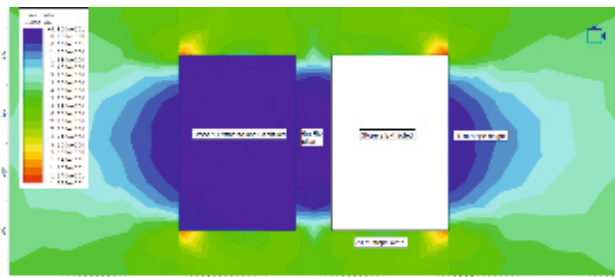


Fig. 2. Horizontal stresses developed in the rib and backfilled column

The Stopping Method- Room and Pillar with Post Pillar

The orebody in the south extremity was quite wide at 60 to 90 m, 15-20 m thick and presence of the various geological disturbances, weak hanging and footwall, water bearing HW and FW strata, friable orebody with intrusion of quartz mica schist, identified water aquifer in the form of Dolomitic Kast. With consideration of all these points and man-entry mine, it was planned the Room and Pillar stoping method with post pillar of 5 m thickness be left out at every opening span of 10 m. The proposed stope dimensions were based on the various studies carried out and planned were: Stope length-30 m, stope height-30 m and stope width not to exceed 20 m at any time during the stoping operation. Fig. 3. shows the schematic layout plan of the proposed stoping method.

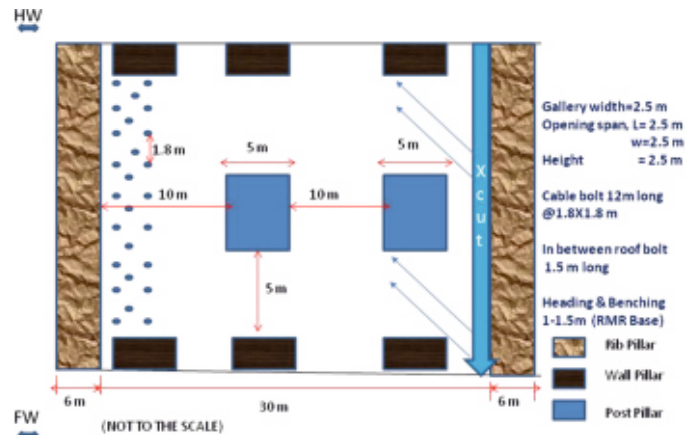


Fig. 3. Schematic of planned parameters of Room and Pillar Mining

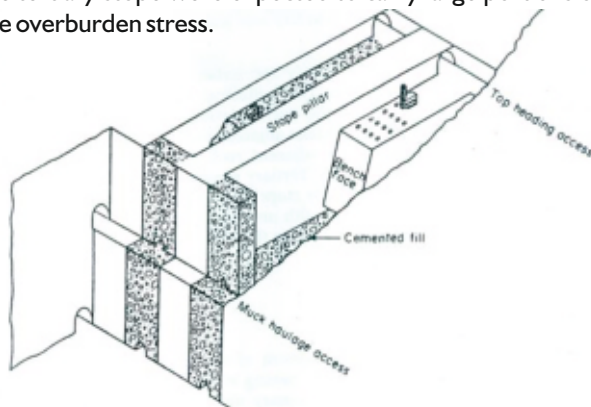
It is proposed that wide ore-body be divided in-between the two parts along the strike direction and main haulage roadway be placed in middle of the ore-body to facilitate the extraction of the ore. Also, to take care of the abutment stresses during the stoping operation, this main haulage roadway be properly supported and provided with the concreting. First, wide ore-body be developed towards Footwall side from the Hanging wall by forming the pillars. Then these formed rooms be retreated back up-side with slicing and then be filled-back using the conventional hydraulic sand as the backfill material. The proposed support system was 12 m long cable bolt with in-between 1.5 m long roof bolts. Thus, estimated support density would be at 0.9 m including cable and roof bolt in-between to take care of the stresses developed. The proposed room and pillar method was one of the variants of the present practised method at this mine which is Horizontal Cut-and-Fill. It was expected that the proposed planned method would help in optimising the recovery and would be adoptable one. Since, it would be mostly mined out as per the present conventional operation of cut-and-fill mining.

Scope for Other Stopping Methods

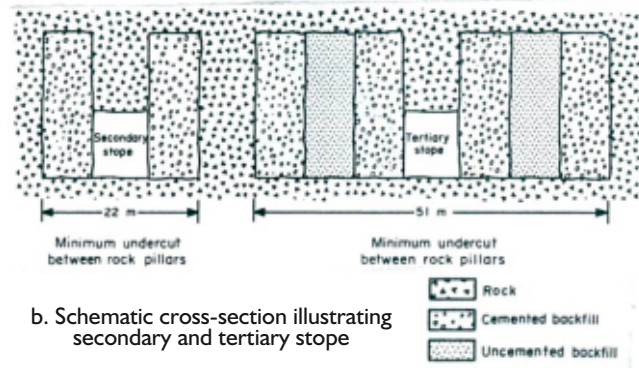
The above suggested method is considered to suit with the existing infrastructure and with any unforeseen difficulties on operational front. However, keeping in view the future growth and increasing demand of good quality ore and emphasis on cent-percent recovery of the valuable and quality ore, the following stopping methods offers the good scope considering the mass production, productivity with economy, enhanced safety and mechanization etc.

Sublevel Bench and Fill Mining

A multi-lift sublevel bench and fill mining offers the good scope for wide ore-body because it allows nearly complete recovery of the ore at relatively high rates of production and provides full overburden support by emplacement of quality strength backfill. The schematic diagram illustrating the sublevel bench and fill mining method is shown in Fig. 4. In this method, primary stopes were backfilled with high-strength cemented fill designed to carry the full weight of the overburden at 50% extraction. The backfilled primary stopes would later become backfill pillars, supporting the roof as the rock pillars were mined. This was achieved by packing the cemented backfill tightly against the hanging wall in the top lift. Recovery of the pillars was performed in a similar manner to the primary stoping. The second, third and fourth lifts were mucked under a fully undercut back using radio remote-controlled LHDs which traversed the length of the stope between backfill high-walls. Mining of the rock pillars were subdivided into secondary and tertiary stopes depending on the stress conditions expected to occur in the backfill pillars. This is illustrated in Fig. 4b, which shows a cross section of two lift stopes. The secondary stope was extracted between two backfill pillars adjacent to the rock pillars. The undercut width was limited to 22 m in this geometry, and the adjacent rock pillars would support the overburden, preventing loading of the cemented backfill. Tertiary stopes were formed between two backfill pillars adjacent to secondary stopes that had been filled with un-cemented fill. The undercut width planned was at 51 m in this geometry, and the backfill pillars forming the walls of the tertiary stope were expected to carry large portions of the overburden stress.



a. Schematic illustration showing the sublevel bench and fill mining method



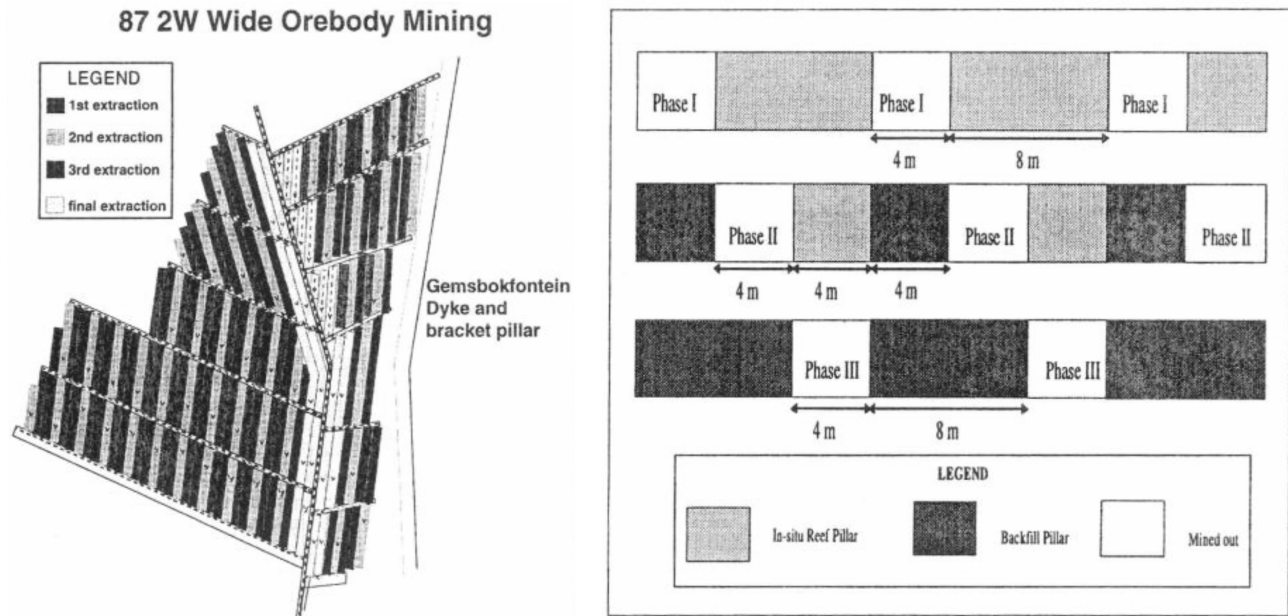
b. Schematic cross-section illustrating secondary and tertiary stope

Fig. 4. Multi-lift sublevel bench and fill mining (Brechtel and Hardy, 1993)

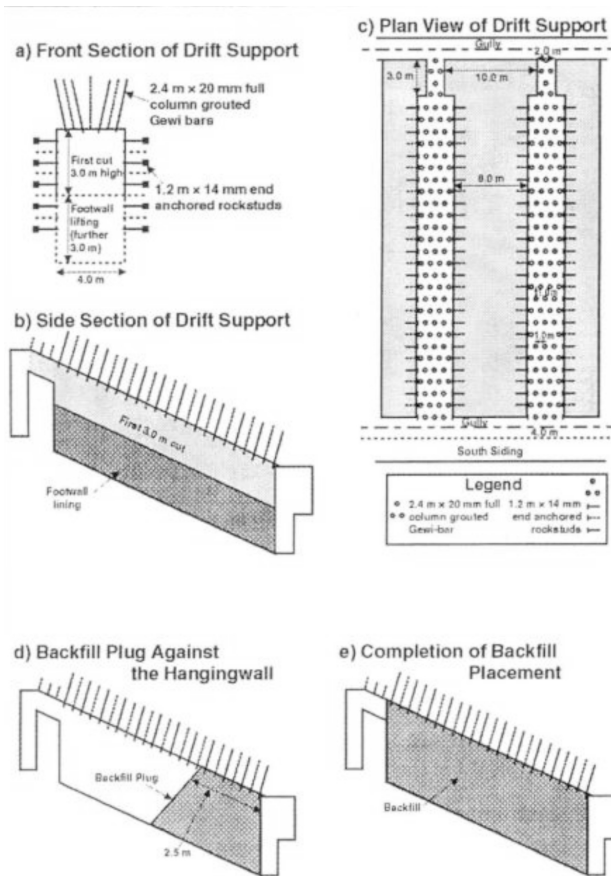
CUSDF Method of Mining for Wide Orebody

The CUSDF mining method is being utilized for the extraction of the wide ore body. A raise is developed conventionally in the centre of the ore body from which reef drives (strike gullies) are spaced 30 m apart. From each reef drive, 4 m wide drifts are mined up-dip along the top reef contact to hole into a reef drive above. Once this is complete, the drift is then footwall lifted to expose the reef package fully. Pillars, whose widths are multiples of the drift width, as shown in Fig. 5, separate the drifts. Once the initial drifts are mined out, backfill is then placed until the drifts are filled tightly. The second scheduled drifts are then mined adjacent to the backfilled drift. It is important to note that these drifts are mined-out using hand-held jackhammers and cleaned by winch-operated scrapers. The support system used in wide ore body mining consists primarily of dowels and tendons. The hanging wall is supported with 2.4 m by 20 mm, full column, grouted dowels, while sidewall support consists of 1.2 m by 16 mm, endanchored rock studs. Due to the nature of the CUSDF mining method, pillars will be created after Phase I extractions (Fig. 5b). Once mined out and ramped, these drifts are then backfilled. The backfilling process requires careful design of bulkhead barricades to allow for hydrostatic pressure when the backfill is placed. This is done using pigtail eye bolts and de-stranded hoist rope. Backfill is placed in 3 m lifts until a 2.5 m long plug is formed against the hanging wall. The drift is then completely backfilled (Fig. 5b). The backfill stands for 28 days to allow curing. During this time, no mining takes place adjacent to any backfilled drifts. The use of backfill is essential to increase the percentage of extraction in the area and also to stabilize the pillars by providing lateral confinement. Shotcrete is occasionally used in areas where friable ground conditions are present. Cemented backfill is used in 60% of the drifts along each drive. As a result of the backfilling requirements, each drift will be mined adjacent to an 8-m-wide pillar with this geometry. Pillar material may vary in nature and may consist of 8 m wide reefpillars (during Phase I), 4m wide backfill and 4m wide reef pillars (during Phase II), or 8m wide backfill places (after Phase II)

(Fig 5a). This sequence is critical to ensure the overall stability.



a. CUDF method for wide orebody mining



b. Support system in the case of CUDF method

Fig. 5. CUDF Mining method for wide orebody
(Singh & MacDonald, 2001)

Conclusions

The wide and thick ore body were associated with the complex geological structure and presence of water aquifers was a daunting challenge for mining. Because of the nature of the ore body, it has been felt that the wide ore body mining method (conventional or with the aid of trackless mining) is the most economical method to adopt. Accordingly, based on the rock mechanics studies and application of empirical and numerical approaches, room and pillar mining with post-pillar was planned for its recovery. Also, future scopes in the form of multi-lift sublevel cut and fill mining and CUDF mining is discussed as a possible high recovery mechanised mining methods for such kind of deposit. It is expected that the proposed mining method will provide invaluable data which will be helpful in planning stoping methods in the case of such wide ore bodies in the future.

Acknowledgment

Thanks are due to M/s MOIL Ltd for sponsoring this study and mine officials for their kind help during the field studies. Thanks, are also due to Dr. A. K. Soni, Dr. M. R. Saharan and Sri B. K. Jha for their help during the course of the study. I take this opportunity to express my sincere thanks to the Director, CSIR-CIMFR for his kind permission to publish this paper. The views expressed therein are of the authors and not necessarily of the Institute.

References

- Bagde M. N. (2014). Numerical study to design stoping operations with sand filling in the case of thick and wide orebody with complex geology. In ARMS8-ISM Int Symp-Rock Mechanics for global issues-National Disasters, Environment and Energy. Sapporo, Japan, 14-16 Oct, Norikazu Shimizu, Katsuniko Kaneko & Jun-ichi Kodama (Eds), 1461-1468.
- Bagde M. N., Jhanwar J. C. & Sangode A. G. (2017). Evaluation of safer stoping parameters at Kandri underground manganese mine of MOIL Ltd with numerical modelling studies. In Proc N_xGnMiFu2017- Int Conf on NexGen Technologies for Mining & Fuel Industries. New Delhi, 15-17 Feb, P. K. Singh, V. K. Singh, A. K. Singh, D. Kumbhakar, M. P. Roy (Eds), Vol. I, 591-596. Allied Publishers New Delhi, ISBN:978-93-85926-40-2.
- Brechtel, C. E. & Hardy, M. P. (1993). Design of pillars with backfill interaction –a case study. In Comprehensive Rock Eng., Vol. II, Hudson J. A. (Chief Editor), Pergamon Press, 711-732.
- Board M., Brummer R. & Seldom S. (2001). Use of numerical modelling for mine design and Evaluation. In Underground Mining Methods-Engineering Fundamentals and International Case Studies. W. A. Hustrulid and R. L. Bullock (Eds), Society for Mining, Metallurgy, and Exploration, Inc:483-492.
- CIMFR Report (2012). Stope Designing of Wide and Thick Orebody in South Extremity of Kandri Mine of MOIL Ltd. Unpublished study report submitted to MOIL Ltd., November.
- IS:11315 (Part 5) (1987). Correlation chart for Schmidt hammer relating rock density, compressive strength and rebound number.
- Laubscher D. H. (1990). A geo-mechanics classification system for the rating of rock mass in mine design. J. S. Afr. Inst. Min. Metall., 90(10):257-273.
- Laubscher D. H. & Jakubec J. (2001). The MRMR Rock Mass Classification for Jointed Rock masses. In Underground Mining Methods-Engineering Fundamentals & International Case Studies. W. A. Hustrulid & R. L. Bullock (Eds), The Society for Mining, Metallurgy, and Exploration, Inc: 475-482.
- Potvin Y. & Hadjigeorgiou J. (2001). The stability graph method for open stope design. In Underground Mining Methods-Engineering Fundamentals and International Case Studies. Edited by W. A. Hustrulid and R. L. Bullock, Published by the Society for Mining, Metallurgy, and Exploration, Inc:513-520.
- Sheorey P. R. (1987). Coal Pillar strength estimation from failed and stable cases. Int. J. Rock Mech. Min. Sci. & Geomech Abstr., 24(6):347-355.
- Singh N. & MacDonald A. J. (2001). Extraction of a wide ore body at depth in the SV2/3 area at Placer Dome Western Areas Joint Venture. In Underground Mining Methods-Engineering Fundamentals and International Case Studies. Edited by W. A. Hustrulid & R. L. Bullock, Published by the Society for Mining, Metallurgy, and Exploration, Inc:179-185.
- Soni A. K., Bagde M. N., Saharan M. R., Prasad N. K. (2017). Hydro-geological study for an underground mine: It is beneficial for mine planning, production and safety. In Proc N_xGnMiFu2017-Int Conf NexGen Technologies for Mining & Fuel Industries. New Delhi, 15-17 Feb 2017, P.K. Singh, V. K. Singh, A. K. Singh, D. Kumbhakar, M. P. Roy (Eds), Vol. I, 97-108. Allied Publishers Pvt. Ltd. New Delhi, ISBN:978-93-85926-40-2.
- Zipf R. K. Jr. (2001). Pillar design to prevent collapse of room and pillar mines. In Underground Mining Methods-Engineering Fundamentals and International Case Studies. Edited by W. A. Hustrulid & R. L. Bullock, Published by the Society for Mining, Metallurgy & Exploration, Inc:493-512.



Comparative analysis of Overhand vs Underhand stoping sequence with cemented pastefill

Rohan Jolly Abraham, Shubham Bhargava, John Loui Porathur, Nageswara Rao Kolikipogu, Rohit Meshram, Vinod Kumar Jagapthal

CSIR-CIMFR Nagpur Research Centre, 17/C, Telangkhedi Area, Civil Lines, Nagpur, Maharashtra, India- 440001

*corresponding author, Email: rohanjolly12@gmail.com

Abstract

Overhand (bottom-up) mining method is commonly adopted in underground mines for extraction of orebodies. It has its advantages and disadvantages based on the geo-mining conditions at the site. However, overhand mining may not be suitable in areas where weak rock mass and high stress environment are observed. Underhand mining can be a better alternative in such scenarios. In this paper an attempt is made to compare the overhand mining method to underhand mining method based on field and numerical modelling studies. FLAC3D software is used to simulate the stress distribution during extraction of ore in both the methods. Accordingly, a comparative analysis was conducted based on numerical modelling results along with field observations obtained through Cavity Monitoring System (CMS) surveys. The study highlights the effectiveness of the underhand mining method in maintaining ground stability in weak, structurally disturbed ground and demonstrates the role of cemented pastefill (CPF) in supporting the hanging wall post-excavation. Overall, the integration of FLAC3D analysis and field CMS data supports the conclusion that, in high-stress weak-rock conditions, switching to underhand stoping with well-engineered CPF can improve safety and extraction.

Keywords: Overhand mining, Underhand mining, FLAC3D, Cemented pastefill (CPF), Numerical modelling, Underground stability.

Introduction

Deep underground mining operations often encounter challenging geotechnical conditions, particularly in deposits hosted within weak rock masses intersected by shear planes. At significant depths, the combination of weak host rock and elevated in-situ stresses greatly increases the risk of instability, including rock falls and stope failures. Conventional overhand stoping method, becomes difficult to execute safely and efficiently due to these adverse ground conditions existing in the roof of the stope under extraction. On the other hand, with advent of pastefill technology, the roof of the stope volume can be replaced with a high strength, uniform and engineered cemented

backfill, that can give better roof stability as compared to the weak rock mass.

The study investigates the comparative performance of overhand and underhand mining methods when supported by engineered high-strength cemented pastefill (CPF). The use of CPF aims to enhance stope stability by providing competent artificial support, thereby mitigating the risks associated with weak rock mass conditions. In overhand mining, the void is progressively filled below each new stope, whereas in underhand mining the cemented fill above acts as a temporary roof for subsequent cuts. Underhand mining was introduced to improve safety in highly stressed ground: miners always work beneath a hardened cemented backfill that can resist rockburst shocks. Numerical modelling using FLAC3D is employed to analyse stress distribution, deformation patterns, and potential failure mechanisms under both mining methods. Numerical modelling is preferred for estimating the strength requirement of a backfill material in a given situation more realistically [1]. FLAC3D is well-suited to simulate paste backfill mechanics under mining-induced loading. The objective of this research is to provide insights into the most suitable mining approach for weak, high-stress environments and to support safer, more productive mine designs.

Site overview & Numerical modelling methodology

The study area is situated in the northern part of India within a prominent metallogenic belt composed of medium to high grade metamorphic rocks of Pre-Aravalli age. The orebody, primarily a lead-zinc deposit, extends along a 17 km strike length within a structurally controlled north-south trending zone. The surrounding lithology includes graphite-mica schist as both hanging wall and footwall rocks. Current workings are at a depth of approximately 700 m, the rock mass exhibits a Rock Mass Rating (RMR) typically ranging from 45 to 60, which corresponds to fair to good quality, though localized weak zones are encountered near faulted areas. The backfill material employed is a cemented pastefill composed of deslimed tailings blended with 8% OPC and water, designed to attain an unconfined compressive strength (UCS) of approximately 1.0 to 1.5 MPa after 28

days of curing.

Numerical analysis was performed using FLAC3D, the model integrated all essential input data, such as rock mass characteristics, in-situ stress parameters and geo-mining conditions, to provide a realistic and dependable assessment of both mining approaches. This comprehensive inclusion ensured that the simulation closely represented actual field condition. The insitu stress was earlier measured using hydro-fracturing technique at the mine site as given below,

$$Sh = \sigma_{xx} = 10 + 0.01 \times H \text{ MPa} \quad (H \text{ is the depth of cover})$$

$$SH = \sigma_{yy} = 12.9 + 0.025 \times H \text{ MPa}$$

$$Sv = \sigma_{zz} = 0.0297 \times H \text{ MPa}$$

Table 1: Rock and pastefill properties used in numerical simulation

Parameter	Rockmass	Pastefill
UCS (MPa)	65-70	1-1.5
Tensile strength (MPa)	1	0.2
Poisson's ratio	0.25	0.25
Young's modulus (GPa)	25	0.73
Cohesion of rock mass (MPa)	3.5	0.5
Angle of internal friction	350	320
RMR	55	-

The 2D model used in which overhand and underhand mining is being implemented is shown in Figure 1 & Figure 2 respectively. In modelling, the stope dimensions of 20 m width, 25 m height, and 700 m depth are used. To capture the rock mass behavior under stress, an elasto-plastic analysis was carried out utilizing the Mohr-Coulomb failure criterion, which has been widely adopted in geo-mechanical modeling due to its simplicity and its capacity to yield reasonably accurate stability predictions.

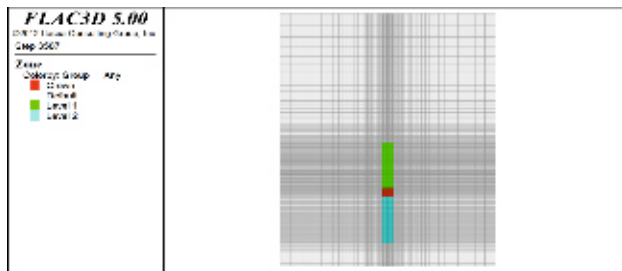


Figure 1: Grid for overhand simulation

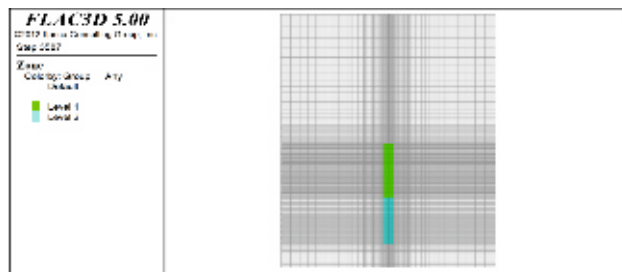


Figure 2: Grid for underhand simulation

The mechanical properties assigned to the cemented paste backfill were derived from a combination of prior laboratory investigations and relevant published literature. Laboratory tests revealed that the friction angle of the backfill material remained relatively stable, even when variations were introduced in uniaxial compressive strength (UCS), cohesion, and Young's modulus. This consistency supported the selection of the Mohr-Coulomb model as an appropriate constitutive framework for backfill representation. To minimize boundary effects and ensure the integrity of the simulation results, the model boundaries were fixed at a distance of around 150 meters from the active stoping area. This spatial buffer helped maintain a realistic stress field around the excavated regions, thereby enhancing the reliability of the predicted deformation and stability outcomes.

The difference between model 1 (overhand) and model 2 (underhand) is the order of extraction. In overhand sequence, modelling proceeds with extraction of level 1 followed by extraction of level 2 (Fig. 1) with crown pillar left in between. Each level is divided in 3 sublevels, starting from the deepest level and proceeding upward. At each level, the lowest stope is mined, pastefill is placed and cured followed by extraction of the upper stope and so on and so forth. In case of underhand sequence, mining starts from the highest level and proceeds downward without leaving a crown pillar. At each level, the uppermost stope is mined and backfilled followed by extraction of the lower stope, always keeping the backfill above as a roof for the next cut.

Numerical modelling results

The overhand mining numerical simulation as shown in figure 3 reveals a higher maximum horizontal stress of approximately 41.7 MPa in the crown. The presence of high stress above the excavation may increase the likelihood of instability. While in the underhand mining scenario shown in figure 6, the peak horizontal stress in the roof reaches around 2.2 MPa. The stress is mainly concentrated below the excavation, with relatively lower stress levels in the roof due to the lower modulus of the pastefill as compared to the rockmass. This suggests a more controlled stress distribution, potentially lowering the chances of failure in the roof in case of underhand mining.

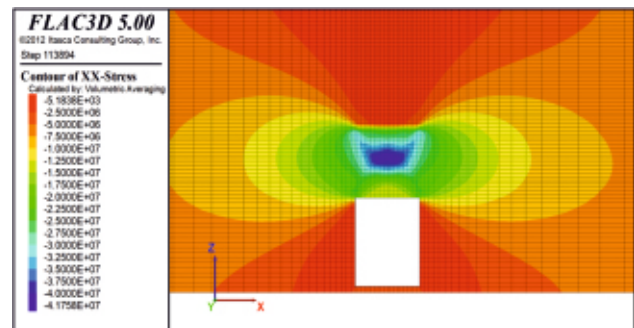


Figure 3: High horizontal stress in overhand mining

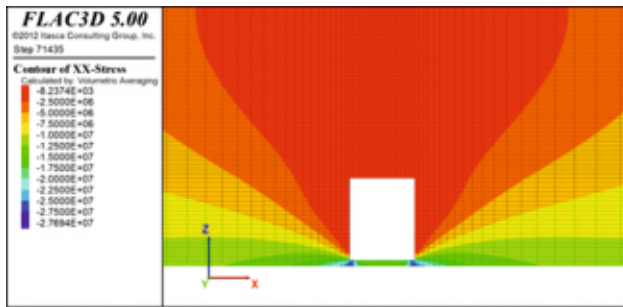


Figure 4: Low horizontal stress in underhand mining

During overhand mining simulation before extracting last sublevel in Level 2 as shown in Figure 5 the failure zones were present in the roof of level to a height of about 6m. After mining the last sublevel, the roof of the stope, which becomes the crown pillar becomes highly unstable as shown in Figure 6.

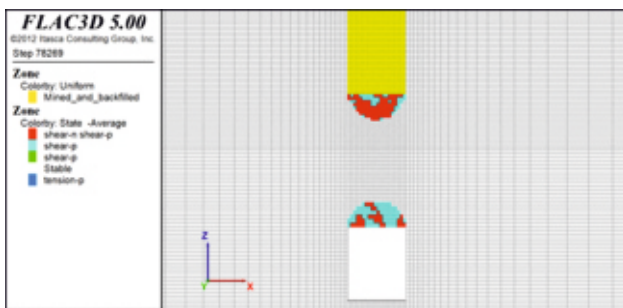


Figure 5: Overhand mining model showing rockmass roof stability & yielding

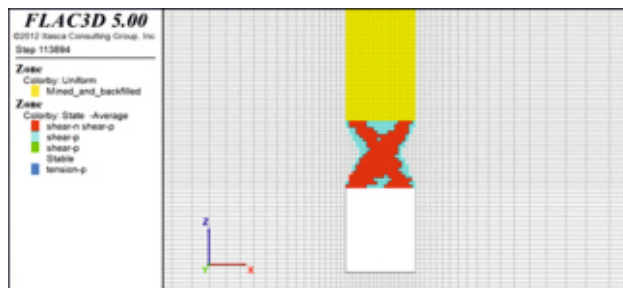


Figure 6: Overhand mining model showing Crown pillar failure

In case of underhand mining, the roof has experienced some failure zones due to the inherent weight of the overlying mass during extraction. Similarly, the floor of the excavation has experienced substantial failure zones due to the concentrated loads from the void as well as the overburden from above.

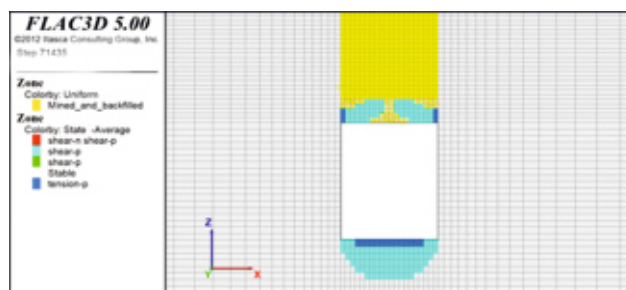


Figure 7: Underhand mining model showing pastefill roof stability and yielding

Field observations

The mine was following overhand stoping method for previous mined out stopes at shallow depths. However, the mine advanced much deeper and this method was found not feasible due to higher stress developments and rockburst. The mine switched to underhand mining at deeper levels. As the stopes are mined out, they are backfilled using pastefill to ensure ground stability and continuity of operations.

Model credibility is supported by field cavity monitoring surveys in an underhand mined out stope. FLAC3D predictions of stope extraction is compared to real measurements from a Cavity Monitoring System (CMS) laser scan. The simulated deformed geometry closely matched the surveyed profile of a stope. This and other studies confirm that FLAC3D can capture realistic trends; the close match increases confidence that the Mohr–Coulomb model and parameters in the modelling are reasonable. Overall, integrating FLAC3D with CMS data enables calibration of strength parameters and provides a valuable field check on predicted failure zones.

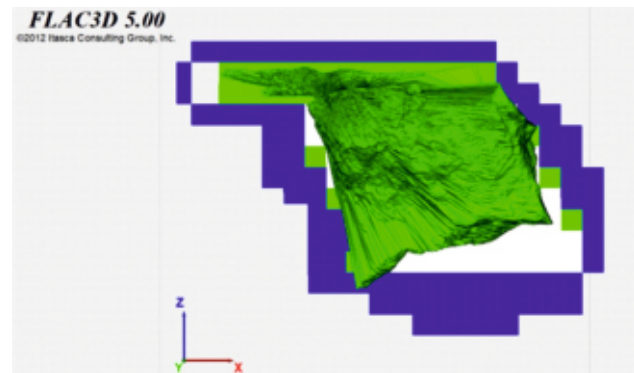


Figure 7: Comparing Failure zones with CMS in underhand mining

Operational and Economic implications

Switching from overhand to underhand stoping in a deep weak-rock mine has major operational impacts. Underhand methods allow recovery of the crown pillar (ore previously left for support), raising total yield. For instance, in a 2017 report it was found that the use of underhand stoping reduced dilution from 14% to 4% while improving recovery rates from 75% to 92% [2][3]. On the flip side, underhand mining required high strength cemented backfill material, which is high capital and operating costs. These add cost, but are offset by higher ore output and safety. Safety benefits are well documented in some reports which show underhand layouts have effectively eliminated rockburst fatalities in several deep mines [4]. Economically, the net benefit depends on ore grade, mining rate, and dilution penalties and much more.

Conclusions

The analysis from Flac3D models and field data highlights the benefits of underhand stoping method with cemented pastefill in weak rock mass and/or in deep mining. Underhand sequences transfer stress downward into the floor rather than upward into roof, reducing rockburst and collapse hazards. Our numerical models are concurrent with previous studies, which predicted stable behaviour for underhand mining using realistic paste strength. Overhand stopes, by contrast, require lower fill strength as they remain in floor & sides, but leave larger crown pillars to avoid failure. The practical outcome is that switching to underhand mining can improve safety and ore recovery in extreme ground conditions. All numerical analyses used Mohr–Coulomb models, which have proven adequate for capturing overall stability. Future work could explore advanced constitutive laws for paste and include time-dependent cure behavior.

References

1. Porathur, J. L., et al. "Stability analysis of a free-standing backfill wall and a predictive equation for estimating the required strength of a backfill material-a numerical modelling approach." *Journal of the Southern African Institute of Mining and Metallurgy* 122.5 (2022): 227-233.
2. Feng, F., Li, D., Li, X., Guo, Z., Wang, S., & Chen, Y. (2017). Novel underhand cut-and-fill stoping method and mechanical analysis of overlying backfill. *Int. J. Geomechanics*, 17(7), 04017004.
3. Yang, P. Y., Li, L., & Aubertin, M. (2017). Numerical and limit equilibrium stability analyses of cemented backfill in vertical stopes. *Int. J. Rock Mechanics & Mining Sciences*, 95, 63–75.
4. Barsoum, K. P. (2013). Underhand cut-and-fill mining as practiced in three deep hard rock mines in the United States. *Mining Engineering*, 65(12), 44–48.
5. Shiels, A., & Sainsbury, D. (2020). Crown pillar extraction with paste underhand stoping. *Proc. Underground Mining Technology (UMT) 2020*, Sheritt, NS, UWA Publ., pp. 223–228.
6. Falaknaz, N., Aubertin, M., & Li, L. (2015). On the stability of exposed backfill in mine stopes. *Proc. 68th Canadian Geotechnical Conference*, Quebec, Canada, 13–16 Oct. 2015, pp. 533–542.
7. Emad, M. Z., Mitri, H. S., & Kelly, C. (2014). Effect of blast-induced vibrations on fill failure in vertical block mining with delayed backfill. *Canadian Geotechnical Journal*, 51(2), 200–212.
8. Liu, G., Li, L., Yang, X., & Guo, L. (2016). Stability analyses of vertically exposed cemented backfill: A revisit to Mitchell's physical model tests. *Int. J. Mining Science and Technology*, 26(6), 1135–1144.
9. Chang, Q., Sun, Y., Leng, Q., Liu, Z., Zhou, H., & Sun, Y. (2021). Stability analysis of paste filling roof by cut and fill mining. *Sustainability*, 13(19), 10899.
10. Mitchell, D. G., & Bowen, R. A. (1982). Stability of backfilled stopes. *Transaction AIME*, 275, 211–220.
11. Li, L., & Aubertin, M. (2012). A revisit of exposed backfill in vertical stopes. *J. of Geotechnical & Geoenvironmental Eng.*, 138(11), 1420–1430.
12. Belem, T., Kassi, A., & Doré, G. (2014). Failure analyses of cemented pastefill exposures using limit equilibrium and numerical methods. *Int. J. Mining Science and Technology*, 24(4), 643–650.



Evaluation of stability of crown pillar during transition from open pit to underground mining- A case study

Aakanksha Sunil Borkar, Saloni Abhay Bhise, Nageswara Rao Kolikipogu, John Loui Porathur, Vinod Kumar Jagapthal
I CSIR-CIMFR Nagpur Research Centre, I 7/C, Telangkhedi area, Civil Lines, Nagpur, Maharashtra, India- 440001
Corresponding author: akankshabrkr@gmail.com

ABSTRACT

As mineral reserves at shallow depths become depleted, the transition from open-pit to underground mining becomes increasingly necessary to access deeper ore bodies. This transition requires determining the optimum size of the crown pillar between the open pit and underground workings to ensure operational safety and structural integrity. Therefore, understanding the behaviour of the crown pillar during underground operations is essential. In this study, a 2D numerical modeling analysis was conducted, considering the actual working conditions of a chromite mine. The shallow ore body is initially extracted through open pit mining a highly friable ore, and the operation then transitions to underground mining by leaving a crown pillar in place. The friable ore and limonitic wall rock mass continues below the open pit to a depth of about -200 m, below which harder rock mass amenable to underground mining is found. Stopping operations are proposed in the competent orebody. An initial trial stope with a height of 25 m was proposed, followed by a regular stope height of 75 m to be implemented after leaving an appropriate crown pillar. FLAC3D software was used to assess stress distribution and the development of plastic zones in the crown pillar during stope extraction. To evaluate the optimum crown pillar thickness, simulations were conducted for thicknesses of 15 m, 20 m, 25 m, 30 m, and 35 m. Based on the numerical modeling results and corresponding Factor of Safety (FoS) values, a crown pillar thickness of 25 m was found to offer a better structural stability and ore recovery. Consequently, this study provides valuable insights for safer and more efficient mine planning during the transition from open-pit to underground mining.

INTRODUCTION

In India and across other parts of the world, a significant proportion of ore deposits are located at increasing depths from the surface. As many open-pit mines approach their economic and geotechnical limits driven by factors such as high stripping ratios, slope stability concerns, and environmental constraints; the transition to underground mining becomes essential for accessing deeper ore reserves

(Dintwe et al., 2022; Verma & Soni, 2024). A critical structure in this transition is the crown pillar-the remnant rock mass situated between the bottom of the open pit and the roof of the underlying underground excavations. The stability of this pillar is vital to ensuring the safety of both surface and underground operations. Failure of the crown pillar can result in severe consequences such as surface subsidence, water inflow, ore dilution, and even catastrophic structural collapse (Verma & Soni, 2024; Carter, 1992; Brady &

Brown, 2006; Martin & Maybee, 2000). Owing to its critical role, crown pillar design has become a central focus in mine transition engineering. Traditional design approaches have often relied heavily on empirical methods. For instance, Bakhtavar et al. (2009) developed regression-based empirical models to estimate optimum crown pillar thickness, while highlighting the lack of universally accepted design standards. However, such empirical models require site-specific calibration and often lack sensitivity to complex geological factors such as heterogeneous rock mass conditions, tectonic stress regimes, and the legacy of previous mining activities (Shnorhokian et al., 2014). To address these limitations, numerical modeling combined with field monitoring has emerged as a powerful tool for assessing the complex geomechanical behaviour of crown pillars. Xu et al. (2019), for example, utilized FLAC3D to simulate artificial crown pillars and demonstrated how optimized designs could improve both stability and ore recovery, especially in deep mining contexts. Likewise, Dintwe et al. (2022) employed advanced 3D numerical tools such as 3DEC to model stress redistribution and potential failure zones, stressing the need to incorporate detailed geomechanical interactions, particularly in weak or fractured rock masses. In the Indian mining sector, crown pillars are often designed using conservative rules of thumb, with limited consideration of local geological conditions. Verma and Soni (2024) emphasized the urgent need for localized studies that combine empirical relationships, in situ stress measurements, and numerical modeling to develop safer and more economically viable crown pillar designs.

This paper presents a comprehensive numerical modeling study with FLAC 3D supported by field observations to evaluate the optimum crown pillar thickness for a mine located in eastern India, where chromite ore is extracted using the blasthole stoping method.

STUDY AREA

The study was conducted at chromite mine, which was initially developed through open-pit mining, extending from the surface elevation of 200 mRL down to the ultimate pit floor at -2 mRL. Exploration data revealed that the rock mass is friable down to approximately -200 mRL, transitioning into a more competent and consolidated rock mass at greater depths suitable for underground mining. Beyond this depth, underground mining was adopted, leaving a crown pillar in place to ensure geotechnical stability between the two mining methods. The caprock extends from the pit bottom to a depth of approximately -275 mRL, beneath which a trial stope has been excavated down to -300 mRL. Following the trial stope extraction, further stoping has been planned to facilitate safe underground extraction and to ensure that design and stability assessment of the intervening crown pillar is required.

The ore deposit is hosted within ultramafic rocks of Precambrian age, predominantly composed of serpentinized peridotite and dunite, with minor occurrences of pyroxenite. The mineralization is stratiform in nature, occurring as discontinuous bands, lenses, and pockets confined within the altered ultramafic units. These ore bodies exhibit a northwest-southeast (NW-SE) strike and dip moderately toward the east. Texturally, the ore varies widely, ranging from lumpy and granular to friable, ferruginous, and disseminated

forms. Geotechnically, the upper rock mass up to approximately -200 mRL is weathered and weak, while the rock mass below this level is competent and lumpy, making it more suitable for underground stoping operations. This transition from weak, weathered overburden to strong bedrock provides a critical context for assessing the stability of the crown pillar.

NUMERICAL SIMULATION & METHODOLOGY

The simulations were carried out using FLAC3D software (Itasca, 2016), which employs the explicit Finite Difference Method for solving geo-mechanical problems. All relevant input data including rock mass properties (Table I), in situ stress conditions, and geo-mining factors were incorporated into the model to ensure a realistic and reliable evaluation of crown pillar performance. For the stope geometry, a 2D numerical grid was constructed with dimensions of 1 m $\times$ 516 m $\times$ 750 m along the x-, y-, and z-axes, respectively as shown in Figure 1, covering the area of interest. The modeling process began with the generation of the mine layout and orebody geometry. The model

domain was stratified vertically into three distinct geological zones based on depth and lithology. Material properties were assigned to each zone, including the weathered rock, ore stopes, paste backfill, and competent surrounding bedrock. Boundary conditions were applied by constraining displacements along the lateral (x and y) boundaries and at the model base, while allowing free movement on the remaining surfaces. Gravity loading was applied using a standard acceleration of 9.81 m/s² to simulate the natural weight of overlying strata. Initially, a virgin elastic model was developed to establish a stable pre-mining stress state. This was followed by 2D elasto-plastic simulations to identify potential yield zones within the crown pillar. To simulate the transition from open-pit to underground mining, the upper excavation (from z = 200 m to z = 20 m) was removed to represent the open-pit void, and equilibrium was re-established. Subsequently, the constitutive model was updated from elastic to elasto-plastic behaviour by applying Mohr-Coulomb parameters including cohesion, friction angle, tensile strength, and density for each geological unit. The stope was then incrementally excavated beneath the crown pillar, and five different crown pillar thickness scenarios were simulated: 15 m, 20 m, 25 m, 30 m, and 35 m. For each case, loose backfill was introduced into the stope zone (from z = -275 m to -300 m). Further excavations were modelled by nulling (removing) and reactivating zones at successively lower depths to replicate the crown pillar geometries under investigation. Throughout the simulation, critical outputs such as induced stresses, shear and tensile failure zones, and displacement patterns were monitored.

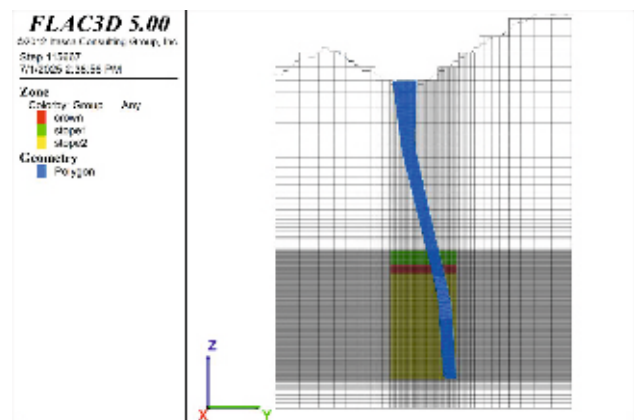


Figure. 1: Two-dimensional grid used for modelling

Table I: Rock mass properties considered for the chromite mine for Mohr-Coulomb elasto-plastic analysis.

Rock mass properties	Stope	Weathered	Backfill
E (Gpa)	15	1	0.149
Poisson's ratio	0.25	0.25	0.25
Density (kg/m ³)	3882	3354	2000
Cohesion (Mpa)	3	-	-
Friction angle(deg)	35	-	-
Tensile Strength (Mpa)	1.2	-	-

The In-situ stress has been determined using hydro-fracturing technique by Mesy (India) Pvt. Ltd. The stress levels used in the current model is

$$\sigma_v = 0.029H \text{ MPa}$$

$$\sigma_h = (2.27 \pm 0.38) + (0.02 \pm 0.001)H \text{ MPa}$$

$$\sigma_H = (4.08 \pm 1.21) + (0.04 \pm 0.004)H \text{ MPa}$$

$$\rho_{\text{mean}} = 2.98 \pm 0.24 \text{ g/cm}^3$$

where H is the depth from surface.

RESULTS AND DISCUSSIONS

Surface crown stability

To assess the stability of the surface crown pillar, a 2D model was run with the pit partially backfilled as shown in figure 2. The results of the stability analysis (figure 2), indicate that rock mass yielding above the upper stoping horizon at -275 mRL is highly localized and limited to a depth of less than 10 m. This limited extent of the yielding indicates that the overlying strata retain sufficient strength and integrity to support the overburden without experiencing significant stress redistribution. Consequently, the crown pillar at the surface is inferred to be geomechanically stable and not expected to trigger the any surface subsidence.

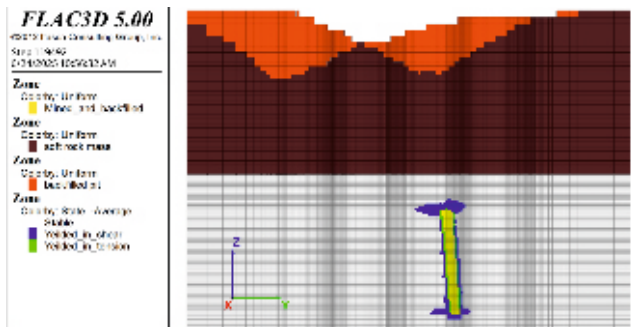


Figure 2: Section view showing stability of the crown pillar after backfilling of the open pit

Inter-level crown stability

The stability of the crown pillar was assessed by monitoring plastic zones and induced stresses at varying thicknesses 15 m, 20 m, 25 m, 30 m, and 35 m. The modeling results indicated that shear failure was the dominant failure mode across all crown pillar thicknesses, as shown in Figure 3. In the case of the 15 m thick crown pillar (Figure 3a), the plastic zones extended throughout the entire thickness, indicating an unstable condition. Yielding was observed approximately 91.96% of the total crown volume in the 15 m pillar model, reflecting a highly stressed condition. A similar type of failure was observed in the 20 m thick pillar (Figure 3b); the failure extended particularly along the sidewalls and at the base with yielding of 92.2%. With an increase in crown pillar thickness to 25 m (Figure 3c), a notable reduction in the concentration of plastic zones was observed, indicating enhanced structural stability. This improvement is further supported by a decrease in the total

yielded volume of the crown to 71.1%. Nevertheless, the overall mechanical stability improved substantially. When the crown pillar thickness was increased to 30 m (Figure 3d), yielding was predominantly limited to areas near the excavation boundary,

indicating enhanced structural stability. The 35 m crown pillar model (Figure 3e) exhibited the most stable conditions among all simulations, with minimal signs of induced failure. The simulations revealed that yielding volumes reduced to 51.3% for the 30 m crown and to 43.9% for the 35 m crown, confirming the stabilizing effect of increased pillar thickness. The percentage yielding with respect to various crown pillar thickness is plotted in figure 3(f).

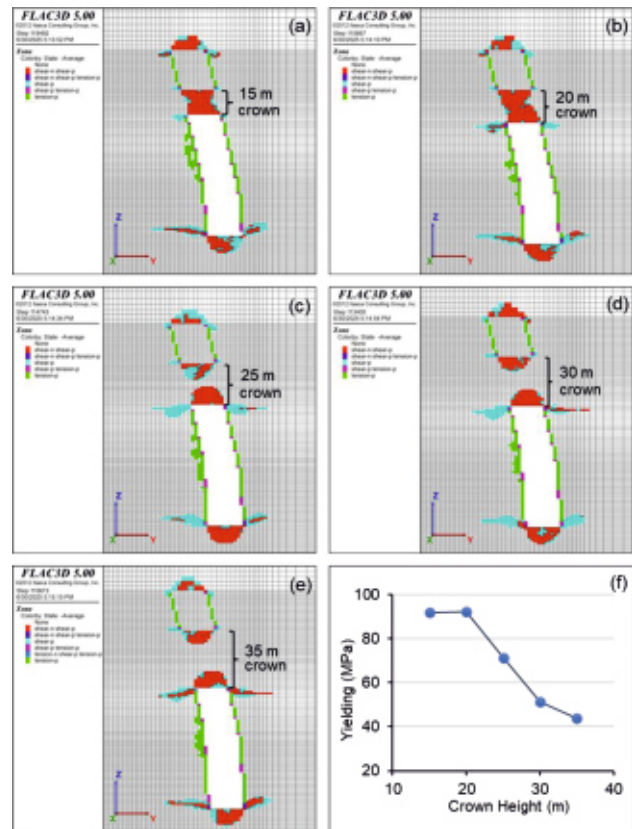
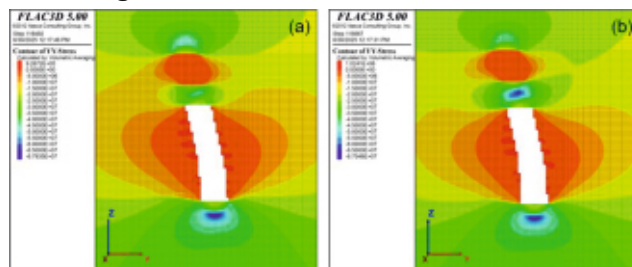


Figure 3: Plastic zones observed in (a) 15 m crown, (b) 20 m crown (c) 25 m crown, (d) 30 m crown, (e) 35 m crown thicknesses, (f) yielding of the crown pillars with respect to crown height.



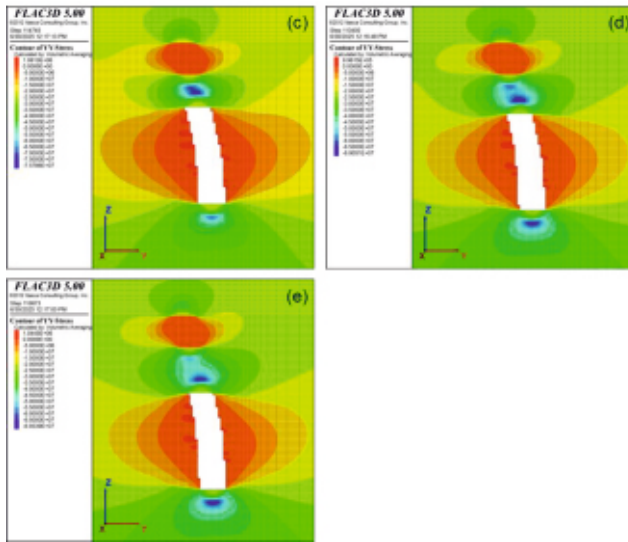


Figure 4: Horizontal distribution of stress in (a) 15 m crown, (b) 20 m crown, (c) 25 m crown, (d) 30 m crown, (e) 35 m crown

Further observations were made from the major horizontal stress distributions, as illustrated in Figure 4. The contours of induced horizontal stress for the 15 m and 20 m thick crown pillars revealed high stress concentrations, particularly along the sidewalls and near the roof (due to tensile stresses). This combination of shear and tensile failure modes critically weakens the structure and increases the risk of collapse. The average major principal stresses observed in the crown pillar were 31.74 MPa, 39.71 MPa, 45.34 MPa, 43.82 MPa, and 42.22 MPa, while the corresponding minor stresses were 4.87 MPa, 8.83 MPa,

11 MPa, 12.35 MPa, and 12.65 MPa for crown thicknesses of 15 m, 20 m, 25 m, 30 m, and 35 m, respectively (figure 5). From the figure it can be said that at about 25 m crown thickness, the pillar is able to hold maximum stress level. The crown pillar goes into significant yielding when the thickness is reduced to less than 25 m as shown in the figure 3.

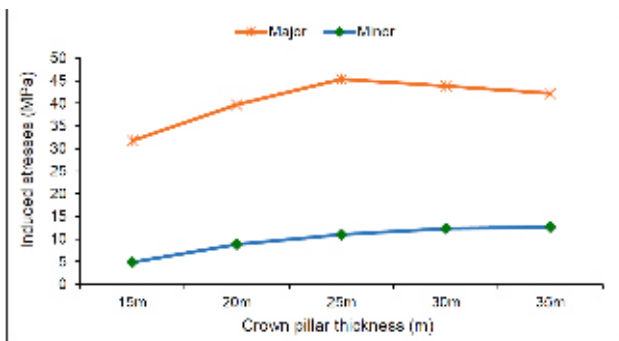


Figure 5: Variation of induced stresses (major and minor) on crown pillar at various thicknesses.

Assessment of FoS of crown pillar

The stability of the crown pillar was further evaluated by calculating the Factor of Safety (FoS) at various thicknesses. In this study, the FoS was determined using the following expression:

$$\text{Factor of Safety (FoS)} = \frac{\sigma_c + \sigma_3 \left(\frac{\sigma_c}{\sigma_t} \right)}{\sigma_1} \quad (1)$$

Here, σ_1 , σ_3 is major principal and minor principal stresses (MPa), σ_c = uniaxial compressive strength (MPa), σ_t = Tensile strength (MPa)

$$\sigma_c = \frac{2c \cos \phi}{1 - \sin \phi} \quad \text{and} \quad \sigma_t = \frac{2c \cos \phi}{1 + \sin \phi}$$

Where, c = cohesion (MPa), ϕ = friction angle of rock mass.

The numerical modeling results exhibited that major and minor principal stresses observed on crown pillar at various thicknesses are 31.74 MPa, 39.71 MPa, 45.34 MPa, 43.82 MPa, 42.22 MPa and 4.87 MPa, 8.83 MPa, 11.0 MPa, 12.35 MPa, 12.65 MPa respectively. After considering the cohesion of 4.5 MPa for rock mass, the UCS and Tensile strength calculated as 17.28 and MPa 4.68 MPa respectively. After substituting these values in Eq. 1, the Factor of Safety deduced as 0.89, 0.99, 1.00, 1.12, 1.184 at 15m, 20m, 25m, 30m and 35m respectively. 0

The combined results from numerical modeling specifically the plastic zone distribution, induced stress contours, and Factor of Safety-indicate that crown pillars with thicknesses of 15 m and 20 m do not provide sufficient stability for safe underground workings. However, crown pillars with thicknesses of 25 m, 30 m, and 35 m exhibit better structural stability. Considering the geo-mining conditions of the mine and aiming to minimize ore loss while maintaining safety, a 25 m thick crown pillar is recommended as the optimum design thickness.

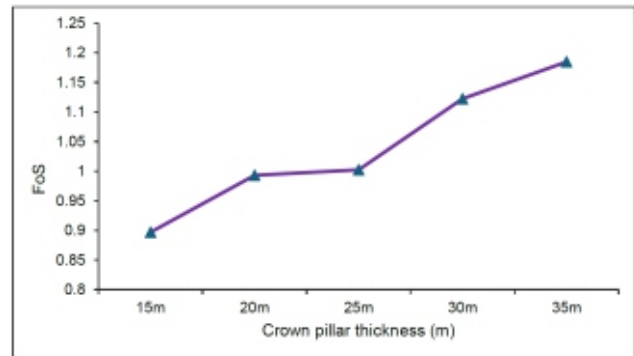


Figure 6: The Factor of Safety (FoS) of crown pillar at different pillar thicknesses

5. CONCLUSIONS

This study investigates the critical aspect of crown pillar stability in a metalliferous mine transitioning from open-pit to underground mining. The findings highlighted the necessity of integrating numerical modeling into crown

pillar design, moving beyond the limitations of traditional empirical approaches. Using a comprehensive parametric simulation framework with FLAC3D, the influence of varying crown pillar thicknesses on overall stability was systematically evaluated. In the context of backfill stoping, a minimum FoS of 1.00 is required to ensure temporary stability. This condition is satisfied when the crown pillar thickness is greater than 25 m.

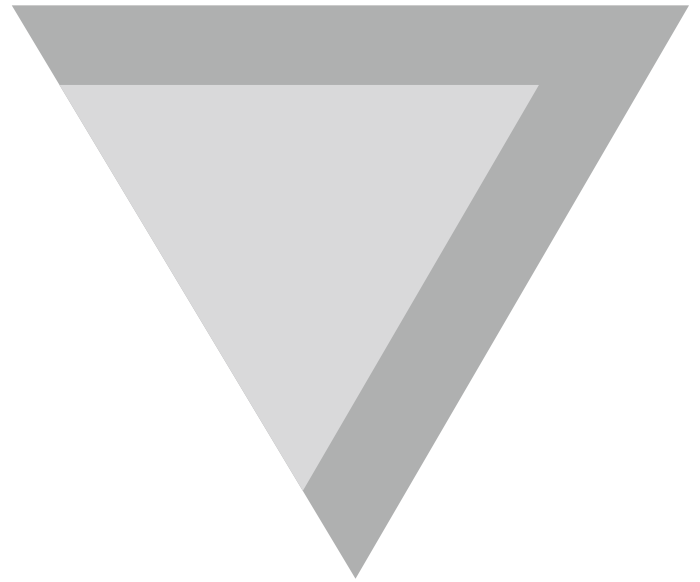
The simulation results consistently indicated that shear failure was the dominant failure mode across all modelled scenarios, with significant stress concentrations particularly along the sidewalls and roof of the crown pillar. However, an increase in crown pillar thickness led to a marked improvement in mechanical stability, reducing the extent of failure zones and yielding behaviour. The percentage yielding of crown pillar reduces to about 51.3% in case of 30 m. In conclusion, a 25 m thick crown pillar was identified as the optimum configuration, offering a balance between geotechnical stability and operational efficiency while minimizing ore loss. These findings not only support safer and more economical mine planning at the study site but also provide valuable guidance for other mining operations undergoing similar transition phases from surface to underground mining.

Acknowledgements

The authors express their sincere gratitude to the Director, CSIR–Central Institute of Mining and Fuel Research (CIMFR), Dhanbad, for granting permission to publish this paper. The authors also thank the mine management for their cooperation and support during the field study. The views and results presented in this paper are solely those of the authors and do not necessarily reflect the official position of their affiliated institution.

References

- Bakhtavar, E., Shahriar, K., & Oraee, K. (2009). Transition from open-pit to underground as a new optimization challenge in mining engineering. *Journal of Mining Science*, 45, 485–494.
- Brady, B. H., & Brown, E. T. (2006). *Rock mechanics: for underground mining*. Springer science & business media.
- Carter, T. G. (1992, June). A new approach to surface crown pillar design. In *Proc. 16th Can. Rock Mechanics Symposium, Sudbury* (pp. 75–83).
- Dintwe, T. K., Sasaoka, T., Shimada, H., Hamanaka, A., Moses, D. N., Peng, M., ... & Onyango, J. A. (2022). Numerical simulation of crown pillar behaviour in transition from open pit to underground mining. *Geotechnical and Geological Engineering*, 1–17.
- Martin, C. D., & Maybee, W. G. (2000). The strength of hard-rock pillars. *International Journal of Rock Mechanics and Mining Sciences*, 37(8), 1239–1246.
- Itasca. 2016. *FLAC3D (Fast Lagrangian Analysis of Continua in 3 dimensions) version 5.0*. Minneapolis: Itasca.
- Shnorhokian, S., Mitri, H. S., & Thibodeau, D. (2014). Numerical simulation of pre-mining stress field in a heterogeneous rockmass. *International Journal of Rock Mechanics and Mining Sciences*, 66, 13–18.
- Verma, M., & Soni, A. (2024). Stability analysis and design considerations for crown pillars in Indian mining conditions. *International Journal of Mining Science and Technology*, 34(1), 45–56.
- Xu, S., Suorineni, F. T., An, L., Li, Y. H., & Jin, C. Y. (2019). Use of an artificial crown pillar in transition from open pit to underground mining. *International Journal of Rock Mechanics and Mining Sciences*, 117, 118–131.



New Age Technologies for Mineral Industry



World's Largest HPGR 30/20 Pioneering Sustainable Iron Ore Plant Design in India

A. Janardhanan-1, T. Mackert-2

1-FLSmidth Private Limited, India

34, Egatoor, Chennai, Tamil Nadu – 603 103, India

2-FLSmidth Mining Technologies GmbH

Rellinghauser Str. 1, 45128 Essen, Germany

Overview: Indian Iron Ore and Steel Industry

India plays a pivotal role in the global iron ore industry, ranking as the fourth-largest producer worldwide. In 2023, the country produced approximately 270 million metric tons of usable iron ore, accounting for around 9.6% of global production. India's iron ore reserves are substantial, with major deposits located in the states of Odisha, Chhattisgarh, Karnataka, and Jharkhand.

India is a major player in the global steel industry, ranking as the second-largest producer of crude steel. In terms of consumption, India's finished steel usage stood at 138.5 million metric tons (MT) in FY24. However, in per capita terms, India lags behind many of its global peers. In 2022-23, India's per capita steel consumption was 119.17 kg – significantly lower than the global average of 221.8 kg and far behind countries like China, where it reached 645.8 kg.

Steel consumption in India is expected to rise, driven by infrastructure development and urbanization. According to ICRA (Indian Credit Rating Agency), domestic steel demand is projected to grow by 9-10% in FY25.

Major Challenges Faced by the Global Mining Industry

The minerals industry faces significant challenges, including the need to process large volumes of low-grade ore at the lowest possible operating cost, along with rising energy prices. These challenges have driven the demand for adopting highly energy-efficient mineral processing systems.

High Pressure Grinding Roll (HPGR) Equipment: Revolutionizing the Mining Industry

High Pressure Grinding Rolls (HPGR) represent an innovative and energy-efficient solution for the mining and minerals processing industry (Picture 1). This technology has gained popularity due to its ability to significantly reduce energy consumption and enhance grinding efficiency.

Over the past several decades, HPGR technology has been

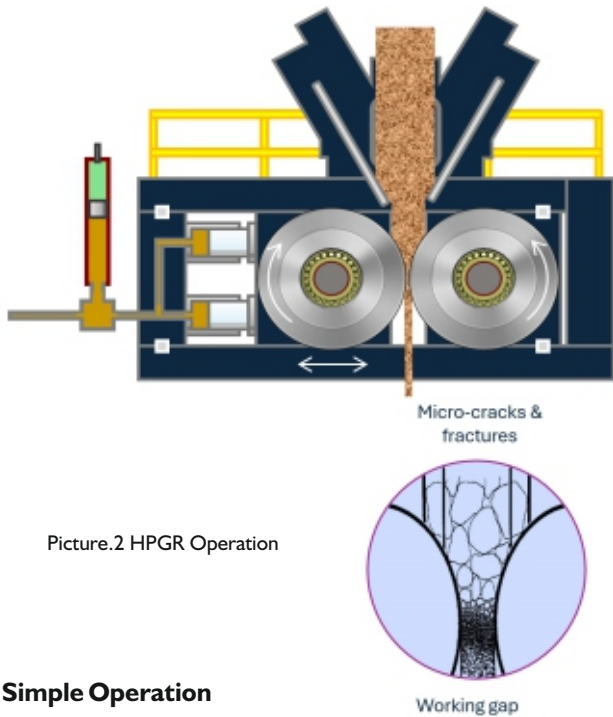
widely accepted by the mining industry as a sustainable alternative to conventional solutions – offering improved process efficiency, better product quality, and reduced energy and wear part consumption. HPGRs are considered potential substitutes for SAG mills or traditional tertiary cone crushers in conventional comminution circuits.



- | | | |
|-----------------------|-------------------------|---|
| 1. Feed chute (lined) | 5. Bearing block | 9. Gear reducers w/ torque arm assembly |
| 2. Feed control gate | 6. Maintenance platform | 10. Cordon shaft |
| 3. Studed Tire | 7. Hydraulic cylinders | 11. Dust enclosure w/ inspection doors |
| 4. Roll shaft | 8. Main drive motor | 12. Roll extraction frame |

What is HPGR?

HPGR consists of two counter-rotating rolls that compress material between them. The high pressure applied to the material induces micro-cracks and fractures, resulting in a more efficient grinding process (Picture 2). This technology is particularly effective for hard and abrasive ores, making it a valuable asset in the mining industry.



Picture.2 HPGR Operation

Simple Operation

The operation of an HPGR is straightforward, as press force and roll speed are the only directly controlled parameters. Operator training is simple, and a new unit can be brought to full production within just a few days. Adjustments to accommodate changes in ore characteristics or plant requirements are also easy to implement.

– Roll speed



– Press force



Applications of HPGR

HPGR technology is highly versatile and is used across a range of applications, including:

- **Mineral Processing:** Widely applied in the processing of minerals such as gold, copper, and iron ore—including pellet feed applications. It is especially effective for hard and abrasive ores.
- **Cement Industry:** Used to grind raw materials and clinker, leading to significant energy savings and

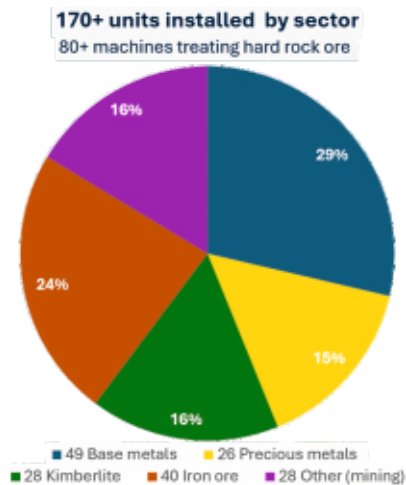
improved product quality.

- **Diamond Liberation:** Employed in the diamond industry to liberate diamonds from kimberlite ore, thereby enhancing recovery rates.
- **Industrial Minerals:** Suitable for processing materials such as dolomite, limestone, and phosphate.

High-pressure grinding rolls (HPGR) are highly efficient machines with versatile applications. In certain cases, HPGRs can achieve reduction ratios of up to 1:1000 when used in finish grinding mode within a closed circuit, paired with suitable air classifiers – demonstrating the remarkable potential of this technology.

Over the past decades, the number of installed HPGR units has grown rapidly across a wide range of applications. As more HPGR-based plants were built, the industry's understanding of the process deepened. This experience enabled continuous optimization – not only of the machine itself but also of the surrounding plant systems – to meet the specific demands of HPGR operation. As a result, HPGRs can now be operated with exceptionally high availabilities, which is particularly critical in the mining industry.

FLS High Pressure Grinding Rolls (HPGR) technology is widely recognized as the global market leader, backed by over 35 years of experience and more than 170 successful operational references across various mining applications (Picture 2).



Picture.2 FLS HPGR install base by sector

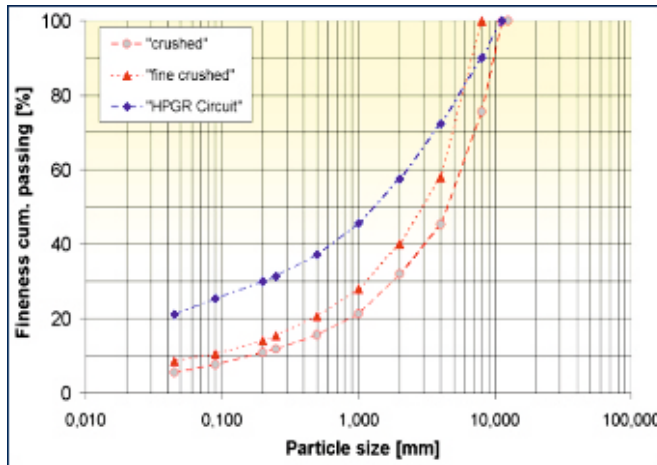
High-Pressure Grinding Rolls (HPGRs) and Verti mills (FTM – FLS Tower Mills) have been successfully introduced into the minerals industry in response to the need for reduced energy consumption. HPGRs are primarily used for tertiary fine crushing of hard and competent ores to sizes ranging from approximately 1 to 10 mm. Together, HPGRs and FTMs represent the most energy-efficient grinding circuit, replacing conventional tertiary crushers and SAG mills in combination with ball mill grinding circuits.

Conventional Tertiary Crushers vs. HPGR Technology

When comparing the product particle size distribution (PSD) of cone crushers and High-Pressure Grinding Rolls (HPGR), several key differences and observations emerge:

1. Particle Size Distribution (PSD):

- Cone Crusher: Typically produces a narrower PSD with a greater proportion of coarse particles. The crushing action is mainly compressive, resulting in larger particle sizes.
- HPGR: Produces a broader PSD with a higher proportion of fine particles. The inter-particle compression characteristic of HPGR leads to more uniform particle sizes and greater generation of fines.



Graph.1 Product PSD comparison of HPGR vs Cone Crusher

1. Energy Efficiency

- Cone Crusher: Generally, less energy-efficient compared to HPGR, especially when targeting higher size reduction. Energy consumption is higher due to the compressive crushing mechanism.
- HPGR: More energy-efficient at higher size reduction targets than conventional crushing methods. The micro-cracks generated in HPGR products reduce the Bond Work Index (BWI), lowering energy requirements in subsequent grinding stages.

3. Micro-Cracks and Liberation

- Cone Crusher: Produces fewer micro-cracks in particles, which can result in lower mineral liberation during downstream grinding processes.
- HPGR: Generates significant micro-cracks in ore particles, enhancing the liberation of valuable minerals and improving the efficiency of downstream processing.

4. Wear and Maintenance

- Cone Crusher: Typically experiences higher wear rates, especially with hard and abrasive materials, leading to

more frequent maintenance and higher operational costs. Crusher availability generally ranges between 75–80%.

- HPGR: Generally, exhibits lower wear rates due to the inter-particle crushing mechanism, resulting in longer-lasting wear components and reduced maintenance needs. HPGRs have demonstrated field-proven availability of over 95%.

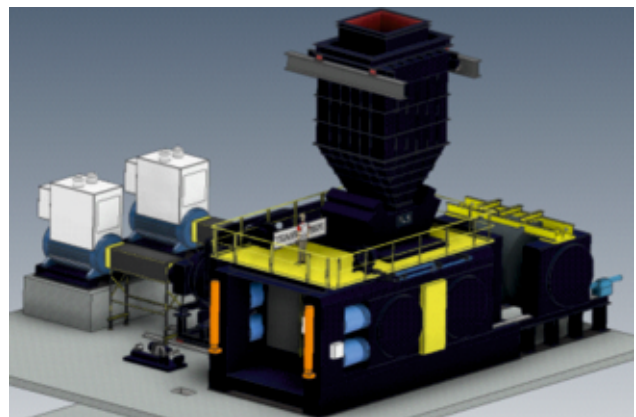
5. Applications:

- Cone Crusher: Commonly used for secondary, tertiary, and quaternary crushing stages in the mining and aggregate industries.
- HPGR: Increasingly used in comminution circuits for hard rock reduction, including applications in diamond, gold, copper, and iron ore processing, including pellet feed applications.

In summary, while tertiary cone crushers are effective in producing a narrow particle size distribution with a lower size reduction ratio, HPGRs offer advantages in energy efficiency at higher size reduction ratios, particle size uniformity, and mineral liberation – making them a valuable addition to modern comminution circuits.

Upcoming Iron Ore Beneficiation Project in India

Lloyds Metals & Energy Limited is developing its prestigious 3 x 15 MTPH BHQ beneficiation project in Hedri, Gadchiroli District, Maharashtra, India. As part of this mega beneficiation project – the first of its kind in India – the world's largest HPGR units 2 nos x 30/20, (Picture 3) have been ordered from FLSmidth Inc. These machines will process lump iron ore feed material from a top size of 50 mm down to less than 3 mm, serving as feed to the subsequent fine grinding stage using the Verti-mill FTM (FLS Tower Mill) system. The total throughput of the HPGR 30/20 machine exceeds 6,000 tph.



Picture.3 World's largest HPGR PM10 30/20 3D model

Laboratory test work on the iron ore feed samples revealed that the Bond Work Index (BWI) of conventionally crushed fresh feed was significantly higher compared to the HPGR centre product. The HPGR centre product material

showed a 17.8% lower BWI, indicating notable energy savings, as shown in Table 1.

Bond Ball Mill Test		Lloyds	WE 008
Sample		conventionally crushed fresh feed	HPGR product M2.4 Center
Closing Mesh Size	µm	100	100
Feed	g	1539	1539
F80	µm	2250	2000
P80	µm	80	77
PI (closing mesh size)	µm	100	100
GIP	g/rev	2.131	2.673
BWI	kWh/st	9.15	7.52
BWI	kWh/mt	10.08	8.29
Relative Bond Index	%	100	82.2

Table.1 Bond Ball mill test result

Trade-off Study: Conventional SAG Mill vs. Secondary Crusher with HPGR Technology

The adoption of HPGR technology in mineral processing has been driven by the demand for energy-efficient comminution solutions. Today, an HPGR trade-off study is a standard part of the due diligence process when evaluating the suitability of SAG milling circuits – particularly for large-scale, hard rock applications with moderate to high power costs. One such trade-off study case is highlighted below in Table 2.

S.No	Major Equipments / Parameters	Option A - SABC	Option B - HPGR-BM	Unit
1	Ore Material	Copper Ore		
2	Specific gravity of the Ore	2.68		m3/t
3	Bond Work Index (BWI)	18.6		kWh/t
4	Production capacity per annum	3.00		MTPA
5	Capacity (Operating / Design)	380 / 420		tph
6	Primary Crusher Output: Feed Size to SAG mill / Cone crusher F80 / F100	150 / 220		mm
7	Secondary Cone Crusher	-	R350	model
8	Installed power	-	275	kW
9	Cone Crusher P80 / P100, feed to HPGR	-	38 / 45	mm
10	SAG mill	24' x 12.5'	-	model
11	Installed power	3500	-	kW
12	Grinding media consumption	2500	-	ton per annum
12	Pebble Crusher	76 / 84	-	tph
13	High Pressure Grinding Rolls (HPGR)	-	PM5 - 17/12	model
14	Installed power	-	2 x 800	kW
15	Product Size from SAG / HPGR P80	-1	-3	mm
16	Ball mill size	Dia. 6.1m x 10m EGL	Dia. 6.4m x 10.5m EGL	model
17	Installed power	6600	7500	kW
18	Final Product size P80	100	100	microns

Table.2 Case study of SAG mill + Ball mill circuit vs HPGR + Ball mill circuit

HPGR products contain micro-cracked particles, which weaken grain boundaries and lower the Bond Work Index (BWI). This reduces the ball milling power required downstream. With a reduced load on the ball mills, there is a substantial decrease in required motor power, lower steel ball consumption, and increased grinding efficiency.

However, in greenfield plant design, the BWI reduction benefits are typically not considered when sizing the ball mills and are only realized during operation. Replacing a SAG mill with an HPGR in primary grinding leads to lower overall power consumption in the comminution circuit.

Table 3: The major capital and operating costs of a secondary cone crusher, HPGR, and a traditional SAG mill with a pebble crusher were assessed and tabulated as a relative index for a case-specific copper ore comminution circuit. The key cost contributors were power consumption and grinding media usage. The reductions achieved in these two areas provide significantly greater benefits than the maintenance costs associated with the secondary crusher and HPGR-ball mill circuit.

Major CAPEX / OPEX Cost Comparison		Secondary Cone	HPGR	SAG* + PC
1	Equipment CAPEX cost	7	78	100
1	Power Cost	6	37	100
2	Grinding media* / Spares Cost	1	12	100
3	Wear Cost	16	66	100
Relative Index of major Operational cost		23	115	300

Table.3 Relative Index of major Capital and Operational cost

Conclusion: Indian Mining – Future Perspective

High Pressure Grinding Rolls (HPGR) technology is transforming the mining and minerals processing industry by offering a more energy-efficient and cost-effective grinding solution. With its numerous benefits and versatile applications, HPGR is poised to become an integral part of modern mining operations.

A Sustainable Solution

An investment in HPGR does more than improve your profit margins – it also helps reduce your carbon footprint. At FLS, we are committed to developing innovative solutions that offer both financial and environmental benefits.

Our HPGR lowers water and energy consumption through its dry processing capability, making it one of the most energy-efficient options for comminution. In addition to saving water and energy, HPGR technology significantly reduces the use of grinding media – eliminating thousands of tonnes annually in SAG mill operations – leading to lower operating costs and a reduced environmental impact.

References

1. Innovation and Technology with HPGR Pro, Experiences and Operating Results in Minerals Applications by T. Mackert.
2. Trade-Off Realities in HPGR vs. SAG Milling – A Practical Comparison of Tropicana and Gruyere Comminution Circuits by Orway Mineral Consultants
3. Test report of Iron Ore sample testing at FLS Germany.
4. Get Insights into the Metals and Mining Industry in India
5. Iron Ore Production by Country 2025
6. Indian Steel Industry Report | IBEF



Applications of Artificial Intelligence (AI), Machine Learning (ML), and the Internet of Things (IoT) in the Mining Industry for Overall Improvement towards Sustainable & Green Mining.

Dhananjay Kumar

Senior General Manager / Head of Mines,
GHCL Limited, Ahmedabad

dkumar@ghcl.co.in, Dhananjay.kumar27092009@gmail.com

Abstract

The mining industry, a critical pillar of global economies, grapples with multifaceted challenges in safety, operational efficiency, resource depletion, and environmental sustainability. The strategic integration of Artificial Intelligence (AI), Machine Learning (ML), and the Internet of Things (IoT) presents revolutionary solutions to address these pressing issues, thereby paving a clear pathway towards the realization of intelligent and green mining practices. This comprehensive paper meticulously explores the diverse and impactful applications of these cutting-edge technologies across the entire spectrum of mining operations, placing particular emphasis on their profound influence on enhancing safety protocols, boosting productivity, optimizing resource management, and robustly protecting the environment. Furthermore, it critically identifies prevailing limitations in their implementation and proposes crucial directions for future research and development.

1. Introduction

The mining industry, foundational to global economies, faces inherent complexities and significant challenges across safety, operational efficiency, resource management, and environmental stewardship. Traditional mining, often labor-intensive and reactive, frequently leads to suboptimal performance, high costs, elevated accident rates, and substantial ecological footprints. The growing demand for minerals, coupled with stringent environmental regulations and societal expectations, urgently necessitates a more sustainable and efficient sector.

The Fourth Industrial Revolution introduces transformative digital technologies, profoundly reshaping industries, including mining. The convergence of Artificial Intelligence (AI), Machine Learning (ML), and the Internet of Things (IoT) marks a pivotal shift in mining operations. These technologies offer unprecedented capabilities for data collection, advanced analytics, intelligent decision-making, and autonomous operation. By harnessing real-time data, predictive insights, and automated control,

mining can transition from traditional paradigms to "intelligent mining" and, critically, "green mining." This paper dissects the application of these technologies, their synergistic impact, and future development directions, aiming to foster a safer, more productive, and environmentally responsible mining future.

2. Artificial Intelligence in Mining Operations

Artificial Intelligence (AI) fundamentally transforms mining by enabling systems to perform tasks requiring human intelligence, including problem-solving, decision-making, and pattern recognition. Its applications are impactful across critical mining areas.

2.1. Predictive Maintenance

AI in predictive maintenance leverages vast datasets from IoT sensors on mining machinery (e.g., vibration, temperature, oil quality). AI algorithms analyze these patterns to accurately predict impending failures, enabling proactive maintenance. This approach significantly reduces unplanned downtime and extends equipment lifespan, leading to substantial cost savings and improved asset utilization. AI can detect subtle anomalies that human operators might miss, triggering early alerts.

2.2. Autonomous Vehicles and Equipment

AI is central to autonomous vehicles and heavy equipment in mining. Operating in hazardous environments like open-pit or underground mines exposes human workers to significant risks. AI-powered autonomous haulage systems (AHS), drills, and loaders navigate complex terrains, perform repetitive tasks with precision, and operate continuously. These systems utilize advanced AI techniques like computer vision for obstacle detection, SLAM for navigation, and reinforcement learning for route optimization. Benefits include reduced human exposure to danger, increased operational consistency and productivity, and optimized fuel consumption, directly enhancing both safety and productivity.

2.3. Resource Exploration and Optimization

AI revolutionizes resource exploration and mine planning. Traditional geological surveys are often time-consuming. AI algorithms process and analyze vast quantities of geological, geophysical, and geochemical data (e.g., seismic, satellite imagery, drilling logs) with superior speed and accuracy. By identifying subtle patterns, AI can pinpoint mineral deposits with higher precision, predict ore grades, and forecast economic viability. This data-driven approach minimizes exploratory drilling, reduces costs, and enables more informed mine planning. AI models can simulate mining scenarios and optimize designs to maximize resource recovery while minimizing waste.

2.4. Safety Monitoring Systems

Safety is paramount, and AI-driven systems significantly enhance worker protection. These systems use real-time video surveillance, wearable sensors (e.g., heart rate, location, gas detection), environmental sensors (e.g., air quality, ground stability), and equipment telematics. AI algorithms continuously monitor these data streams to detect hazards in real-time. Examples include computer vision identifying unauthorized personnel or unsafe behaviors, and spotting early signs of geological instability. AI also analyzes accident patterns to identify root causes and predict high-risk scenarios. By providing immediate alerts and actionable insights, AI minimizes accidents and fosters a safer work environment.

3. Machine Learning in Mining Operations

Machine Learning (ML), a powerful subset of AI, forms the analytical backbone for intelligent mining. ML algorithms process large datasets, identify intricate patterns, and make data-driven predictions. This capability is indispensable for enhancing operational efficiency, resource utilization, and environmental compliance.

3.1. Ore Grade Estimation and Processing Optimization

ML significantly improves ore grade estimation accuracy, vital for efficient extraction and processing. By analyzing geological data, drill core assays, and sensor data from ore sorters, ML models predict mineral concentrations. This precision allows selective extraction of higher-grade material, optimizing blending and minimizing waste processing. ML also optimizes mineral processing plants by predicting optimal parameters for crushing, grinding, flotation, and leaching based on real-time data, increasing recovery rates, reducing energy, and optimizing reagent use.

3.2. Enhanced Predictive Maintenance

ML is the core engine for pattern recognition in predictive

maintenance. Models are trained on equipment operational parameters, maintenance logs, and failure histories. Techniques like regression, classification, and anomaly detection predict component degradation. For instance, supervised learning classifies equipment states, while unsupervised learning detects unusual anomalies. This enables proactive maintenance, preventing catastrophic failures, reducing unscheduled downtime, and extending asset life, leading to significant cost savings.

3.3. Advanced Exploration and Geological Modeling

ML boosts mineral exploration efficiency. Geoscientists input vast geological, geophysical (magnetic, gravity, seismic), and geochemical data into ML algorithms. These identify subtle patterns associated with mineral deposits, performing data fusion to create comprehensive geological models. This leads to more targeted exploration, reducing costly drilling. ML also performs spatial analysis and predictive mapping, forecasting mineral probabilities in unexplored areas based on known geological contexts.

3.4. Refined Safety Monitoring and Risk Prediction

ML models refine safety monitoring. By continuously analyzing real-time data from environmental monitors (e.g., methane), wearable devices (e.g., proximity, vital signs), and video feeds, ML algorithms identify escalating risks. They can detect unusual gas concentrations, deviations from safe procedures, or predict ground instability from seismic patterns. Models trigger immediate alerts to workers and supervisors, enabling rapid response. Analyzing historical accident data, ML identifies high-risk areas, informing safety protocols.

3.5. Operational Optimization and Process Control

ML algorithms optimize complex mining processes by learning from historical performance. This includes refining drilling and blasting for optimal fragmentation, and minimizing wear and energy. ML analyzes parameters like drill depth, explosive type, and rock characteristics to recommend optimal blast designs. In materials handling, ML optimizes conveyor speeds, truck loading, and routing. For beneficiation plants, ML dynamically adjusts process parameters (e.g., reagent dosage) in real-time for optimal performance and recovery, adapting to changing ore characteristics.

3.6. Environmental Monitoring and Impact Mitigation

ML supports environmental monitoring and mitigation, aligning with green mining principles. Analyzing continuous data from environmental sensors (e.g., air/water quality, noise, dust, ground stability), ML models detect deviations from standards and identify risks. ML can predict dust dispersion or contaminant leaching, allowing proactive measures to prevent pollution, ensure regulatory

compliance, and reduce ecological footprint. ML also optimizes water management by predicting demand and supply, leading to reduced consumption and efficient recycling.

4. The Internet of Things (IoT) in Mining Operations

The Internet of Things (IoT) provides the foundational layer for intelligent mining, enabling ubiquitous, real-time data collection through a vast network of interconnected physical devices and sensors. These devices, embedded in machinery, infrastructure, the environment, and personnel, offer unprecedented visibility and control. Continuous data gathering transforms reactive management into proactive, data-driven decision-making.

4.1. Remote Monitoring of Equipment and Environmental Conditions

IoT sensors allow comprehensive remote monitoring of critical assets and environmental parameters across mining sites. This includes monitoring heavy machinery performance (engine temperature, fuel, tire pressure) and environmental factors (mine slope stability, air/water quality). Data transmits wirelessly to a central platform, enabling supervisors to oversee operations, identify issues immediately, and dispatch teams efficiently, reducing physical inspections in hazardous zones.

4.2. Enabling Predictive Maintenance through Sensor Data Analysis

IoT is key to predictive maintenance by providing the raw data for AI and ML. Sensors in machines collect data on vibrations, heat, pressure, and lubrication. Accelerometers detect subtle changes indicating bearing wear, and thermal cameras spot overheating. This continuous data stream allows early detection of anomalies and deviations, which are precursors to equipment failure. Without widespread IoT deployment, sophisticated AI/ML predictive capabilities would be impossible.

4.3. Enhanced Safety Monitoring via Wearable Devices

IoT wearable devices revolutionize worker safety. Miners wear smart helmets, vests, or wristbands with sensors. These monitor physiological parameters (heart rate, vital signs), track real-time location (crucial underground for proximity detection and emergency response), and detect falls or impacts. If a worker deviates from a safe zone, nears machinery, or has a health emergency, the IoT device automatically alerts a control room. This instant communication and tracking improve emergency response and enable proactive accident prevention.

4.4. Improved Asset Tracking and Logistics

IoT enables precise asset tracking throughout the mining value chain. RFID tags, GPS trackers, and other IoT devices on equipment, tools, and ore wagons monitor location, status, and utilization. This provides real-time inventory, reduces loss, and optimizes logistics, ensuring equipment availability. In the supply chain, IoT tracks materials from extraction to processing, improving transparency and efficiency.

4.5. Energy Management and Environmental Sensing

IoT sensors optimize energy consumption. By monitoring real-time electricity usage of pumps, ventilation, and processing equipment, IoT identifies waste and suggests optimizations. Smart ventilation in underground mines adjusts fan speeds based on air quality, leading to significant energy savings. A dense network of environmental IoT sensors monitors ground stability, water levels, air quality (dust, gases), and noise. This ensures compliance with regulations, identifies ecological impacts, and enables proactive mitigation, directly supporting green mining.

4.6. Facilitating Autonomous Operations

IoT provides the critical data backbone for AI-driven autonomous operations. Autonomous haul trucks rely on LiDAR, radar, cameras, and GPS receivers (all IoT devices) to perceive surroundings, navigate, and avoid obstacles. The continuous data stream feeds AI systems for real-time steering, acceleration, and braking decisions. In autonomous drilling, IoT sensors provide data on rock hardness and progress, allowing AI to optimize parameters. By supplying accurate and timely data, IoT minimizes human exposure to danger and ensures consistent, optimized autonomous system operation.

5. Synergistic Integration: AI, ML, and IoT for Intelligent Mining

The true transformative power in mining stems from the profound synergistic integration of AI, ML, and IoT. This convergence creates a sophisticated, closed-loop intelligent system that continuously collects data, derives insights, makes informed decisions, and enacts optimized actions, forming the bedrock of intelligent and green mining practices.

5.1. The Data-Driven Ecosystem

IoT devices act as the ubiquitous nervous system of the mining operation, meticulously collecting vast quantities of raw, real-time data from every corner of the mine: subterranean sensors (geological stress, gas levels), wearable devices (worker vitals, location), and instruments on heavy machinery (performance, fuel, component health). This diverse data stream—structured numerical

readings, unstructured video/audio—is continuously transmitted to a central processing hub.

This raw data is then processed by Machine Learning algorithms. ML models clean, process, and analyze this data at scale, performing crucial tasks:

- **Pattern Recognition:** Identifying trends and anomalies indicating equipment wear, geological instability, or unsafe practices.
- **Predictive Analytics:** Forecasting future events like equipment failure, resource demand, or environmental compliance risks, based on historical and real-time data.

Classification: Categorizing data points (e.g., ore grades, rock types, normal/abnormal equipment operation).

- The insights generated by ML serve as critical inputs for Artificial Intelligence systems. AI, building on ML patterns and predictions, performs higher-level cognitive functions:

Intelligent Decision-Making: AI algorithms leverage ML-derived insights to make real-time optimized decisions, far exceeding human capacity (e.g., optimal maintenance time, drilling parameter adjustments, autonomous vehicle rerouting).

Automated Action and Control: Based on these decisions, AI systems initiate automated actions: dispatching maintenance crews, adjusting machinery controls, issuing alerts, or guiding autonomous systems.

5.2. Closed-Loop Optimization Examples

- This integrated approach creates continuous feedback loops, leading to perpetual optimization:

Predictive Maintenance Loop: IoT sensors on a haul truck transmit vibration/temperature data. ML analyzes it, detecting a consistent increase in bearing temperature and specific vibration frequencies, predicting high failure probability. AI cross-references schedule, resources, and truck criticality, then schedules maintenance during a low-impact window and orders parts automatically. Post-maintenance, IoT confirms repair, and the cycle continues, learning from interventions.

Operational Efficiency Loop: IoT sensors on conveyor belts provide real-time throughput and energy consumption. ML analyzes this to identify inefficiencies or blockages. AI adjusts belt speed, optimizes material routing to processing units, or suggests comminution changes based on ore hardness variations detected by other IoT sensors and ML analysis. This dynamic adjustment ensures optimal throughput and minimal energy waste.

Environmental Sustainability Loop: IoT environmental sensors (dust monitors, water quality probes) feed data to

ML models. ML identifies a rising trend in particulate matter near a residential area, predicting air quality standard exceedance if operations continue. AI automatically triggers dust suppression adjustments, modifies blasting schedules, or temporarily reduces activity in affected areas to prevent environmental breach. This proactive approach ensures regulatory compliance and minimizes ecological impact.

- This synergistic integration transforms mining into a smart, interconnected, responsive ecosystem, enabling real-time adaptation, predictive capabilities, and autonomous execution, pushing the industry towards unprecedented levels of safety, productivity, and sustainability.

6. Practical Relevance and Real-World Case Studies

- Real-world case studies powerfully substantiate the advantages of integrating AI, ML, and IoT in mining, highlighting the practical benefits of intelligent mining practices.

Rio Tinto's Autonomous Operations and Robotics: Rio Tinto is a leader in AI-powered autonomous operations. Their "Mine of the Future" in Pilbara features autonomous haulage systems (AHS) transporting iron ore 24/7. These AI-guided trucks dramatically increase safety by removing personnel from hazardous areas and boost productivity through consistent operation and optimized routing. Rio Tinto also uses AI robots for dangerous mine inspections, improving safety and collecting precise infrastructure data, demonstrating AI's dual enhancement of safety and efficiency.

BHP Billiton's Productivity and Cost Reduction: BHP Billiton extensively leverages AI and ML to optimize operations, reporting significant productivity gains and cost reductions. Analyzing datasets from drilling, blasting, and material handling, ML algorithms identified inefficiencies and optimal parameters. ML models predict equipment downtime, optimize maintenance, and improve ore body knowledge, leading to efficient extraction. These strategies boosted overall productivity by an estimated 10% and cut costs by 5%, showcasing direct economic impact.

Freeport-McMoRan's Copper Recovery Enhancement: Freeport-McMoRan implemented AI-driven optimization in processing plants to enhance copper recovery. AI algorithms analyze real-time sensor data from flotation cells and grinding mills. By continuously monitoring parameters like pulp density and reagent dosage, AI dynamically adjusts controls to maximize copper yield. This advanced optimization resulted in a notable 5% enhancement in copper recovery, directly impacting profitability and resource efficiency.

Anglo American's Water Management and Sustainability: Anglo American demonstrates

commitment to environmental sustainability by integrating AI and ML into water management. AI and ML models analyze real-time data from IoT sensors monitoring water levels, consumption, and quality. These models predict water demand, optimize recycling, and identify reduction opportunities. This data-driven approach achieved an impressive 20% reduction in water consumption, highlighting these technologies' role in meeting environmental targets and advancing green mining.

- These case studies collectively illustrate that AI, ML, and IoT are not theoretical but actively deliver tangible, measurable benefits across mining, from enhancing safety and productivity to ensuring environmental responsibility.

7. Limitations and Future Research Directions

- Despite advancements, widespread adoption and optimal implementation of AI, ML, and IoT in mining face significant challenges. Addressing these is crucial for unlocking the full potential of intelligent and green mining.

7.1. Prevailing Limitations

- **Data Quality, Volume, and Integration Issues:** AI/ML effectiveness depends on data quality and consistency. Mining generates vast, heterogeneous data from disparate systems (legacy and modern), leading to silos, inconsistent formats, missing values, and noise. Integrating these diverse datasets into a unified, clean, and reliable source remains a major hurdle. Data integrity and real-time validation are critical.
- **High Implementation Costs and ROI Justification:** Deploying AI, ML, and IoT infrastructure (sensors, networks, computing, software) requires substantial capital. This upfront investment can deter companies, especially smaller ones. Quantifying ROI in a complex, long-lifecycle industry like mining requires a long-term perspective and robust financial modeling, which is challenging.
- **Cybersecurity Concerns and Data Privacy:** Increased reliance on IoT devices and cloud-based AI/ML exposes mining to heightened cybersecurity risks (operational disruptions, data theft, safety compromises). Robust cybersecurity, including data encryption, secure networks, and intrusion detection, is paramount. Data privacy concerns, particularly with wearable worker devices, demand careful consideration and regulatory adherence.
- **Workforce Transition and Ethical Considerations:** Automation driven by AI and robotics raises concerns about job displacement and the need for significant workforce reskilling. The industry must manage this

transition proactively, investing in training for new skills required to operate, maintain, and oversee these technologies. Ethical considerations include transparency of AI decisions, accountability for autonomous system failures, and potential algorithmic bias.

7.2. Future Research Directions

- Future research should strategically overcome these limitations to accelerate AI, ML, and IoT adoption in mining.
- **Development of Robust and Adaptive Algorithms:** Research must focus on resilient AI/ML algorithms that handle mining's dynamic, complex, and unpredictable nature. This includes algorithms performing well with imperfect/noisy data, adapting to changing geological conditions, and learning from operational shifts. Explainable AI (XAI) is crucial for trust and understanding among operators.
- **Enhanced Data Standardization and Interoperability:** A critical area is developing industry-wide data standards and protocols for seamless data exchange and interoperability between systems, vendors, and platforms. This enables effective data integration and reduces complexity. Research into blockchain for secure data provenance could also be beneficial.
- **Advanced Cybersecurity Solutions for Industrial IoT (IIoT):** Future research must develop specialized, robust cybersecurity solutions for IIoT in mining, including edge computing security, secure firmware updates, anomaly detection, and self-healing architectures to protect critical infrastructure.
- **Human-AI Collaboration and Workforce Reskilling Models:** Future research needs to explore optimal human-AI collaboration, designing intuitive interfaces and effective training for the evolving workforce. Researching strategies for managing workforce transition and job creation in AI-enabled mining is essential. Addressing social/ethical implications, including responsible AI deployment frameworks, is also paramount.
- **Sustainable AI and Energy Efficiency:** As AI models grow complex, computational demands and energy consumption increase. Future research should focus on developing more energy-efficient AI algorithms and hardware, contributing to green mining by reducing the carbon footprint of digital transformation itself.

By proactively addressing these challenges through focused research and collaboration, the mining industry can ensure a smoother transition toward a truly intelligent, safe, and environmentally responsible future.

8. Conclusion

The mining industry is undergoing a profound transformation, driven by the strategic integration of Artificial Intelligence (AI), Machine Learning (ML), and the Internet of Things (IoT). These technologies are not merely incremental but represent a paradigm shift, enabling the industry to effectively tackle critical challenges in safety, operational efficiency, resource optimization, and environmental sustainability.

The widespread deployment of IoT sensors provides unprecedented real-time data collection, creating a ubiquitous digital nervous system. This rich data stream fuels Machine Learning algorithms, which process, analyze, and extract invaluable insights, identifying patterns, making accurate predictions, and enabling proactive problem-solving. Building on these insights, AI systems then perform complex decision-making and orchestrate autonomous actions, optimizing processes, enhancing safety, and driving

operational excellence.

This synergistic interplay creates a powerful, self-optimizing ecosystem promising a safer, more productive, and environmentally responsible future for mining. Real-world case studies from industry leaders like Rio Tinto, BHP Billiton, Freeport-McMoRan, and Anglo American demonstrate tangible benefits: improved safety, significant productivity gains, enhanced resource recovery, and substantial environmental impact reductions.

While the journey toward a fully intelligent and sustainable mining sector is evolving—marked by data quality issues, high costs, cybersecurity vulnerabilities, and ethical concerns—the path forward is clear. Continuous research and innovation are crucial, focusing on robust algorithms, data standardization, cybersecurity, and addressing social/ethical implications. By embracing these advancements and confronting hurdles, the mining industry is well-positioned for long-term.

Need of R&D and AI application for Aggregate & Sand Industry in India

Dr. Ramesh Murlidhar Bhatawdekar^{1,2, 3}, Prof. Dr. Trilok Nath Singh⁴, B.R.V. Suheel Kumar⁵, Bhola Singh⁶, Anil Banchhor⁷, Anurag Jain⁸, Prof. Dr. Rahul Ralegaonkar⁸, Sanchita Nawale⁹

¹ Department of Mining Engineering, Indian Institute of Technology, Kharagpur 721302

² Geotropik, Faculty of Civil Engineering, Universiti Teknologi Malaysia, Skudai (81310)

³ Global Aggregate Information Network, Ireland

⁴ Director, Indian Institute of Technology, Patna.

⁵ OSD to the Government of Telgana, Mines and Geology Department & VCMD, TGMDC, Former Director of Mines and Geology

⁶ Former CMD, Northern Coal Fields Ltd (NCL)

⁷ MD& CEO, RD Concrete, Mumbai

⁸ Head of Aggregates, Ultratech Cement, Mumbai

⁹ VNIT, Nagpur

Abstract:

As compared to the last century, the demand of aggregate and sand has increased exponentially during the last 25 years in India reaching 6 Billion T per annum. Aggregate industry has undergone substantial change from Manual breaking to mechanised crushers upto 250 TPH. There is urgent need to declare "Aggregate and Sand" as minerals of National Importance. Government should grant large size mining leases so that aggregate producers can produce 1 to 10 MTPA from single lease which help industry producing quality products. IIT's & NIT to support R&D activities for better products. Research on critical minerals, Rare Earth Elements (REE) and Alkali Silica Reaction (ASR) are essential. Research is also required based on experimentation and application of AI. Aggregate and Sand Industry needs National Association to meet various challenges. National Association can become a member of Global Aggregate Information Network (GAIN) for transfer of technologies, best practices.

Key words: Aggregate Industry, Alkali Silica Reaction, Global Aggregate Information Network (GAIN). R&D,

Introduction:

Global demand of aggregate has sky rocketed reaching 42 Billion T in 2021 [1,2]. Demand of aggregate and sand have increased several fold touching 6 Billion T for India during 2014-25. Aggregate and sand represent highest consumption of natural resource (4.2 T per Capita consumption per year in India). 11.21 lakh crore (US\$ 128.64 billion) are allocated for infrastructure development during Union Budget 2024-25. Infrastructure projects include highways, airports, seaports, bridges and flyovers in many Urban areas. Aggregate and sand are major raw materials and back bone of any key infrastructure projects.

Historically since 1947, Aggregate and sand mainly used for housing and local asphalt roads which were obtained locally. 'Aggregate and sand are minor minerals and are not given national importance. Leases granted are limited to 5 Ha and thus limiting production capacity of any aggregate quarry.

On the other hand, nearby developing nations surrounding India such as Thailand, Malaysia, Indonesia, Cambodia have aggregate quarries producing 1 to 5 MTPA. On the other hand, China equivalent in size of India, has aggregate quarries producing 10 to 100 MTPA from aggregate quarries. Aggregate and M sand produced are transported by Belt Conveyor or through waterways, railways to the destination such as Metro city or infrastructure projects. After transporting aggregate or M sand long distance, the same is distributed through smaller vehicles for local consumption.

Figure 1 shows development of aggregate industry in India since 1980. During initial era aggregate was produced by breaking boulders manually provided by contractor. During last 15 years, 250 TPH crushers are used to produce aggregate and Manufactured Sand (M Sand). Latest technology of air classification is evolving. Quarry sizes are increasing from 0-5 acres to 25-30 acres in the different sizes of the country. Over the years, usage of M Sand has increased during the last two decades in Metro and 2 tier cities in India for construction purpose.

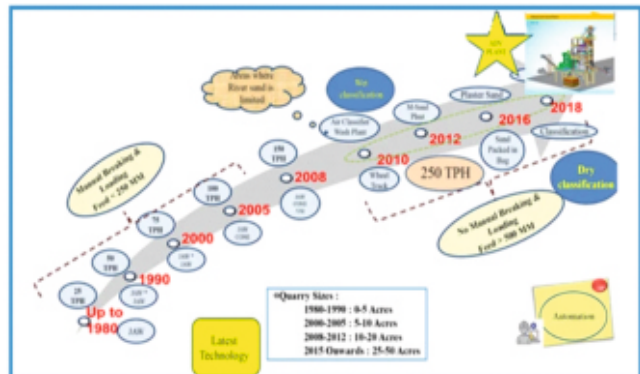


Figure-1: Development of Aggregate Industry in India since 1980 [3]

This paper discusses various opportunities for R&D and AI application for Aggregate and Sand Industry in India.

Need of R&D for Aggregate and Sand Industry:

R&D centres for aggregate and Sand Industry attached to IIT and NIT across country are necessary due to the following consideration.

- (i) Aggregate and sand still remains unorganized sector and to meet construction requirement, R&D centres are necessary for having quality of aggregate and sand to product development.
- (ii) Building material is used for Urban areas to low-cost housing for rural areas. Aggregate and sand are main components for developing different building material applications. In Urban Areas, there may be requirement of decorative items. On the other hand, for low cost building material is required for rural areas.
- (iii) Alkali Silica Reaction (ASR) may be concern for critical structures, underground structures. Such type of research requires long term experimentation
- (iv) Aggregate and sand are used in large quantities for construction and infrastructure industry. Any research study needs to be undertaken whether critical or rare earth minerals are present in aggregate & sand areas
- (v) Metro cities and 2 tiers cities in India, buildings are aging and redevelopment of several buildings needs to be done. R& D is necessary -How recycled aggregates can be produced in different parts of the country.
- (vi) Resource Management: R&D can promote sustainable extraction practices, ensure the long-term availability of aggregates and sand while minimizing environmental impact.

R&D in concrete and Ready-Mix concrete

Traditional Portland cement concrete, which is extensively utilized in civil engineering projects, contributes notably to greenhouse gas emissions. This impact arises from the production of its key components, including the cement binder, coarse and fine aggregates, and the chemical reactions that occur during cement hydration [4]. According to the findings presented by Mo et al [5] The cement industry is responsible for approximately 5% of global CO₂ emissions. To address this, geopolymers concrete (GPC) has emerged as a significant innovation in the concrete sector aimed at lowering carbon dioxide emissions in civil engineering. Geopolymer concrete is created through a geopolymerization process that uses aluminosilicate materials such as fly ash, metakaolin, and steel slag combined with alkaline activators like sodium hydroxide and/or sodium silicate.[6]. Incorporating fly ash or steel slag in the production of geopolymer concrete significantly lowers CO₂ emissions compared to traditional cement, reducing them by as much as five to six times.[7]. Because of these benefits, this cement-free alternative material has attracted significant interest from researchers globally due to its environmental and economic advantages.

Geopolymer concrete has been effectively used in various structural applications, including beams, columns, slabs, tunnel linings, and pavements. This is primarily because GPC demonstrates mechanical properties comparable to those of traditional Portland cement concrete[8]. Typically, three main approaches are widely employed to predict compressive strength, with computational modeling being one of them. [9] One commonly used method to predict compressive strength is the parametric multi-variable regression model, which analyzes multiple variables simultaneously to establish their relationships with the strength outcome [10] or the method based on artificial intelligence techniques [11] Among these methods, artificial intelligence (AI) techniques have been widely adopted by researchers in civil engineering over the past twenty years. [12] Data-driven techniques, particularly artificial neural networks (ANN) and fuzzy logic (FL), have gained popularity due to their strong predictive capabilities across various engineering fields. [13] Both ANN and FL models were created to predict the 7-, 28-, and 90-day compressive strength of fly ash-based concrete. The study gathered data on several input variables such as water, sand, and fly ash contents, with compressive strength as the output, collected from previous research. The trained multilayer neural networks showed strong potential in predicting compressive strength, with a minimum coefficient of determination (R^2) of 0.96. However, the study did not analyze the relationship between material composition and mechanical strength, which is important for assessing how input factors affect concrete properties. In a separate study, Prasad et al [14]. Replacing a portion of cement with Class F fly ash supports sustainability and reduces greenhouse gas emissions. To predict the compressive strength of self-compacting concrete (SCC) containing Class F fly ash, various machine learning models were developed using a dataset of 327 samples. Seven input variables, including six concrete components and sample age, were used. Models tested include regression trees (RT), Gaussian process regression (GPR), support vector regression (SVR), and artificial neural networks (ANNs). The ensemble ANN model achieved the highest accuracy, with a mean absolute error (MAE) of 4.37 MPa and a correlation coefficient (R) of 0.96. Other models like multi-gene genetic programming (MGGP) and RT showed similar or slightly lower accuracy, with MGGP having an MAE of 5.70 MPa and R of 0.93, and RT an MAE of 6.64 MPa and R of 0.89. [15] Fine aggregate obtained from rivers is known as river sand, while crushed hard granite or sandstone used as coarse aggregate is called gravel; together, these are referred to as natural aggregates (NA). Their engineering properties have made them standard materials in construction. For decades, their use has been favoured due to well-established guidelines. However, these resources are finite and currently face a crisis because their consumption is outpacing natural replenishment. Being the most in-demand materials, their demand is expected to double by 2060, reaching 55 gigatons[16]. The situation is

serious. In many regions worldwide, the supply chains for these natural materials are complicated and often linked to illegal activities. To promote sustainability and foster a circular economy, various industrial by-products such as fly ash, bottom ash, blast furnace slag, construction and demolition waste, shredded tires, glass aggregate, and others have shown potential as substitutes for natural aggregates in multiple applications. Similarly, overburden (OB) waste rocks are also being explored as viable alternatives to natural aggregates.

Coalmine overburden aggregates

The term "coalmine overburden" (OB) describes the waste rock removed during surface coal mining. This material poses challenges for coal mining industries, as managing these dumps demands significant financial resources and extensive land. Additionally, occasional failures of these dumps can result in loss of life and property. However, OB has found useful applications such as in brick manufacturing, as backfill material, sub-ballast in road construction, base and subbase layers, and as fine aggregate in concrete.[17]

India's fast-paced urbanization and infrastructure growth have created an enormous demand for construction materials like sand and aggregates, which are crucial for concrete used in roads, buildings, bridges, and other structures. However, excessive extraction of these natural resources has resulted in serious environmental problems, including riverbank erosion, groundwater depletion, loss of habitats, and alterations to the landscape. Moreover, the quality of locally available materials often varies significantly, posing difficulties in maintaining consistent concrete quality [18].

Need of AI application for Aggregate and Sand Industry

Research and development (R&D) combined with AI applications could significantly benefit the aggregate and sand industry in India in several ways:

Efficiency in Extraction: AI can optimize extraction processes by analysing geological data to identify optimal sites and predict resource availability.

Quality Control: AI can enhance quality control measures, ensuring consistency in particle size, gradation, shape, and cleanliness of aggregates, which are crucial for construction materials.

Predictive Maintenance: AI-driven predictive maintenance can reduce machinery downtime used in mining and processing, improving overall operational efficiency.

Market Demand Forecasting: AI can analyse market trends and predict demand fluctuations, helping producers optimize their production schedules and inventory management.

Environmental Monitoring: R&D can develop AI tools

for real-time environmental monitoring to comply with regulations and minimize the ecological footprint.

Automation of Processes: AI can automate routine tasks in production and logistics, lowering labor costs and improving safety in hazardous environments.

Research and development (R&D) combined with AI applications could significantly benefit the aggregate and sand industry in India in several ways:

- **Efficiency in Extraction:** AI can optimize extraction processes by analysing geological data to identify optimal sites and predict resource availability.
- **Resource Management:** R&D can promote sustainable extraction practices, ensuring the long-term availability of aggregates and sand while minimizing environmental impact.
- **Quality Control:** AI can enhance quality control measures, ensuring consistency in particle size, gradation, shape, and cleanliness of aggregates, which are crucial for construction materials.
- **Predictive Maintenance:** AI-driven predictive maintenance can reduce machinery downtime used in mining and processing, improving overall operational efficiency.
- **Market Demand Forecasting:** AI can analyse market trends and predict demand fluctuations, helping producers optimize their production schedules and inventory management.
- **Environmental Monitoring:** R&D can develop AI tools for real-time environmental monitoring to comply with regulations and minimize the ecological footprint.
- **Automation of Processes:** AI can automate routine tasks in production and logistics, lowering labor costs and improving safety in hazardous environments.

Artificial Intelligence (AI) offers a promising approach to address these challenges by improving the characterization, quality control, and sustainable use of both natural and alternative construction materials. Advanced AI techniques including supervised machine learning methods like Random Forests and Support Vector Machines, deep learning models such as Convolutional Neural Networks, and optimization strategies like Genetic Algorithms and Multi-Objective Optimization process large datasets on the physical and chemical properties of aggregates and substitute materials. This enables accurate prediction of concrete performance parameters like compressive strength, durability, and workability, allowing engineers to efficiently design optimized concrete mixes.[19]

Significantly, India's construction industry is progressively adopting recycled and industrial by-product materials to minimize environmental damage and conserve natural resources. Materials such as coal mine overburden

the rock and soil excavated to reach coal seams fly ash from thermal power plants, steel slag, and crushed concrete from demolition waste are increasingly used as supplementary aggregates. However, these materials vary greatly in characteristics like particle shape, mineral composition, and contamination levels, which can influence concrete performance if not thoroughly assessed[20]

AI techniques assist in overcoming these challenges by analyzing complex datasets to evaluate the suitability of such materials. For instance, clustering algorithms can categorize materials with comparable properties, while regression models forecast how recycled aggregate features impact concrete strength. Additionally, machine learning can determine the most effective preprocessing or treatment methods like adjusting particle size or removing contaminants to enhance the quality of coal mine overburden aggregates.[21-22]

From an environmental standpoint, AI-driven optimization promotes more sustainable mining and material processing methods. Predictive models can simulate different extraction scenarios to minimize damage to landscapes and lower carbon emissions. By enhancing the utilization of recycled and waste materials in concrete production, AI reduces reliance on virgin aggregates, thereby decreasing the environmental harm caused by quarrying and riverbed mining. Additionally, this approach helps manage industrial waste by redirecting materials such as coal mine overburden and fly ash away from landfills and illegal dumping sites, thereby reducing pollution and land use problems [23]. Reducing clinker content by substituting it with supplementary cementitious materials is the most practical, efficient, and readily adoptable approach in the ready-mix concrete industry[24].

Various supplementary cementitious materials (SCMs) such as fine limestone, fly ash, ground granulated blast furnace slag, silica fume, volcanic ash, calcined clay, rice husk ash[25], bagasse ash, waste glass sludge, and nano-silica have been explored as potential clinker replacements to produce more sustainable cement and concrete. Among these, granulated blast furnace slag (GBFS), a byproduct of the iron industry[26], and fly ash (FA), from thermal coal plants, have been the most widely used alternatives in recent decades. Currently, about 20% of cement consists of SCMs, mainly fine limestone, GGBFS, and FA[23]. Globally, around 330 million tons of FA and 900 million tons of GBFS are available annually. Numerous studies have examined the effects of replacing cement with varying proportions of FA and GGBFS on the mechanical and durability properties of concrete. Research indicates that incorporating FA and GGBFS generally enhances both the mechanical strength and durability of concrete, especially at later curing stages[27]. Compressive strength, a key mechanical property, exhibits a complex nonlinear relationship with the mix composition, which becomes

even more intricate when incorporating these sustainable materials[28].

Moreover, AI-driven decision support tools help policymakers and planners predict future construction material needs, assess resource availability, and pinpoint environmentally sustainable areas for extraction and waste reuse. This facilitates strategic, long-term planning that balances economic development with environmental responsibility.

In conclusion, the incorporation of AI in managing natural, recycled, and alternative materials such as coal mine overburden and industrial by-products is propelling India's construction sector toward greater efficiency, cost savings, and sustainability. By enhancing material quality prediction, encouraging waste reuse, optimizing extraction processes, and reducing environmental impacts, AI plays a vital role in developing resilient infrastructure while preserving natural resources and safeguarding ecosystems.

Recommendations and conclusion:

- (i) Aggregate and Sand minerals should be considered of National Importance considering huge demand for infrastructure and construction industry.
- (ii) Aggregate and Sand producers to get large size leases so that they start producing 1 to 10 MTPA from single lease and meet demand of industry
- (iii) Alternative transport of aggregate and sand through waterways, railways and dedicated roadways to be developed along with large size aggregate quarries
- (iv) R&D activities for aggregate and sand industry to be promoted through IIT, NITs to meet demand of industry, develop new products. Possibility of extracting Critical minerals, REE elements to be looked into. ASR is a matter of concern for aggregate and sand. Adequate research to be done in different parts of the country.
- (v) Aggregate and Sand subjects to be introduced in Civil and Mining Engineering colleges across different parts of the country so that expert manpower is available.
- (vi) AI to be used for aggregate & sand industry as continuous improvement tool.
- (viii) There is a need of formation of Aggregate, sand, gravel association at national level to meet various challenges of the industry.
- (vii) Aggregate and Sand Industry needs National Association to meet various challenges. National Association can become a member of Global Aggregate Information Network for transfer of technologies, best practices from other parts of the world.

References

- [1] www.gain.ie
- [2] Chea, Kwang-Seok, et al. "Study on the Trend of Aggregate Industry." *Korean Journal of Mineralogy and Petrology* 36.2 (2023): 135-145.
- [3] Bhatawdekar, R. M., Mohamad, E. T., Singh, T. N., Chengong, D. H. S., Kainthola, A., Khandelwal, M., ... & Azad, M. A. (2025). Towards sustainable sand resource management-Best governance practices and alternatives to river sand in India. *Environmental Science and Pollution Research*, 32(21), 12551-12578.
- [4] C.-K. Ma, A. Z. Awang, and W. Omar, "Structural and material performance of geopolymer concrete: A review," *Constr. Build. Mater.*, vol. 186, pp. 90-102, 2018.
- [5] K. H. Mo, U. J. Alengaram, and M. Z. Jumaat, "Structural performance of reinforced geopolymer concrete members: A review," *Constr. Build. Mater.*, vol. 120, pp. 251-264, 2016.
- [6] A. Ménez, J. L. Provis, G. C. Lukey, A. Palomo, P. van Deventer, JannDuxson, and F.-J. S. J., "Geopolymer technology: the current state of the art," *J. Mater. Sci.*, vol. 42, pp. 2917-2933, 2007.
- [7] B. C. McLellan, R. P. Williams, J. Lay, A. Van Riessen, and G. D. Corder, "Costs and carbon emissions for geopolymer pastes in comparison to ordinary portland cement," *J. Clean. Prod.*, vol. 19, no. 9-10, pp. 1080-1090, 2011.
- [8] M. G. Girish, K. K. Shetty, and A. Rao Raja, "Self-consolidating paving grade geopolymer concrete," in *IOP Conference Series: Materials Science and Engineering*, IOP Publishing, 2018, pp. 92006.
- [9] Y. Lin, C.-P. Lai, and T. Yen, "Prediction of ultrasonic pulse velocity (UPV) in concrete," *Mater. J.*, vol. 100, no. 1, pp. 21-28, 2003.
- [10] G. F. Kheder, "A two stage procedure for assessment of in situ concrete strength using combined non-destructive testing," *Mater. Struct.*, vol. 32, pp. 410-417, 1999.
- [11] G. Trtnik, F. Kavčič, and G. Turk, "Prediction of concrete strength using ultrasonic pulse velocity and artificial neural networks," *Ultrasonics*, vol. 49, no. 1, pp. 53-60, 2009.
- [12] S. Lai and M. Serra, "Concrete strength prediction by means of neural network," *Constr. Build. Mater.*, vol. 11, no. 2, pp. 93-98, 1997.
- [13] A. A. Elshafey, N. Dawood, H. Marzouk, and M. Haddara, "Crack width in concrete using artificial neural networks," *Eng. Struct.*, vol. 52, pp. 676-686, 2013.
- [14] B. K. R. Prasad, H. Eskandari, and B. V. V. Reddy, "Prediction of compressive strength of SCC and HPC with high volume fly ash using ANN," *Constr. Build. Mater.*, vol. 23, no. 1, pp. 117-128, 2009.
- [15] M. Kovačević, M. Hadzima-Nyarko, I. N. Grubeša, D. Radu, and S. Lozančić, "Application of Artificial Intelligence Methods for Predicting the Compressive Strength of Green Concretes with Rice Husk Ash," *Mathematics*, vol. 12, no. 1, 2024, doi: 10.3390/math12010066.
- [16] O. (2019). G. M. R. O. to 2060. G. M. R. O. To. and A. from <https://doi.org/10.1787/9789264307452-en>, Global Material Resources Outlook to 2060. 2019. doi: 10.1787/9789264307452-en.
- [17] A. Mishra, S. K. Das, and K. R. Reddy, "Processing Coalmine Overburden Waste Rock as Replacement to Natural Sand: Environmental Sustainability Assessment," *Sustain.*, vol. 14, no. 22, 2022, doi: 10.3390/su142214853.
- [18] D. Suresh and S. Chawla, "Comparative life cycle assessment of railway subballast layer with natural and coal overburden aggregates in India," *Int. J. Life Cycle Assess.*, vol. 27, no. 5, pp. 704-718, 2022.
- [19] A. Grbeš, "A life cycle assessment of silica sand: comparing the beneficiation processes," *Sustainability*, vol. 8, no. 1, pp. 11, 2015.
- [20] G. Rebitzer et al., "Life cycle assessment: Part 1: Framework, goal and scope definition, inventory analysis, and applications," *Environ. Int.*, vol. 30, no. 5, pp. 701-720, 2004.
- [21] K. Khan, B. A. Salami, M. Iqbal, and M. N. Amin, "Compressive Strength Estimation of Fly Ash / Slag Based Green," vol. 15, no. 3722, 2022.
- [22] K. M. Skarżyńska, "Reuse of coal mining wastes in civil engineering—Part 2: Utilization of minestone," *Waste Manag.*, vol. 15, no. 2, pp. 83-126, 1995.
- [23] L. Poudyal and K. Adhikari, "Environmental sustainability in cement industry: An integrated approach for green and economical cement production," *Resour. Environ. Sustain.*, vol. 4, pp. 100024, 2021.
- [25] N. Ankur and N. Singh, "Performance of cement mortars and concretes containing coal bottom ash: A comprehensive review," *Renew. Sustain. Energy Rev.*, vol. 149, pp. 111361, 2021.
- [26] Y. Jiang, T.-C. Ling, K. H. Mo, and C. Shi, "A critical review of waste glass powder—Multiple roles of utilization in cement-based materials and construction products," *J. Environ. Manage.*, vol. 242, pp. 440-449, 2019.
- [27] A. A. Raheem and B. D. Ikotun, "Incorporation of agricultural residues as partial substitution for cement in concrete and mortar—A review," *J. Build. Eng.*, vol. 31, pp. 101428, 2020.
- [28] K. Scrivener, F. Martirena, S. Bishnoi, and S. Maity, "Calcined clay limestone cements (Lc3)," *Cem. Concr. Res.*, vol. 114, pp. 49-56, 2018.
- [29] P. Akpinar and A. Khashman, "Intelligent classification system for concrete compressive strength," *Procedia Comput. Sci.*, vol. 120, pp. 712-718, 2017.

Can Space Mining Support a Sustainable Future ?

Daksha Vyas, Pratik Godbole and Kirtikumar Randive

Post Graduate Department of Geology, RTM Nagpur University

Correspondence: prateek15godbole@gmail.com

Space mining has emerged as a potential solution to growing resource scarcity on Earth, particularly considering increasing demand for rare metals and the pressures of sustainable development. The idea involves extracting valuable materials such as platinum-group metals and rare earth elements from celestial bodies including asteroids, the Moon, and Mars. Proponents argue that space mining could support long-term space exploration, reduce dependence on terrestrial resources, and unlock new economic opportunities. However, significant technical, legal, environmental, and ethical challenges remain. This paper presents a futuristic scenario of space mining, highlighting recent technological advances in robotic exploration, in-situ resource utilization, and asteroid targeting; and evaluating them on the uncertainties around cost, feasibility, and

environmental impact. This paper also examines the current legal frameworks, particularly the Outer Space Treaty, and the lack of clear international consensus on ownership and resource rights. The potential for inequality in access, ecological disturbance in extraterrestrial environments, and unintended geopolitical tensions is critically discussed. The paper argues for a cautious and cooperative approach that encourages innovation while prioritizing sustainability, equity, and long-term planetary stewardship.

Keywords: Space mining, sustainable development, outer space resources, environmental impact, intergenerational equity, space governance, ethical exploration, off-Earth resource use.





Transforming Mining Waste into Sustainable Nano- materials: Techniques, Applications and Economic Potential

Kaustubh Deshpande-I, Pratik Godbole-I and Kirtikumar Randive-I*

I Post Graduate Department of Geology, RTM Nagpur University, Nagpur

Correspondence*: randive101@yahoo.co.in

Abstract

Mining operations generate substantial volumes of waste that pose persistent environmental and economic challenges. Recent advancements in nanotechnology and circular economy frameworks have enabled the transformation of these waste materials into high-value nanomaterials. This paper explores a range of physical, chemical, and biological methods, including hydrothermal synthesis, green biosynthesis, sol-gel processes, and electrochemical techniques, for converting mining and electronic waste into functional nanoparticles. These nanomaterials exhibit versatile applications in sectors such as medicine, agriculture, construction, energy, and environmental remediation. The economic implications are equally compelling, offering new revenue streams, reducing waste management costs, and supporting sustainable industrial development, particularly in post-mining regions. This interdisciplinary approach not only contributes to resource recovery and environmental stewardship but also reinforces the role of nanotechnology in achieving long-term sustainability goals.

Keywords: Mining waste, Nanomaterials, Sustainable synthesis, Circular economy, Environmental remediation

Introduction

The mining industry, while vital to modern economies, generates vast quantities of solid and liquid waste that pose significant environmental and health hazards. However, an emerging paradigm shift rooted in sustainability and circular economy principles has reimagined mining waste as a valuable resource for the synthesis of nanomaterials (Nms). These high-surface-area materials, known for their unique physicochemical properties, offer transformative applications in energy, catalysis, remediation, and electronics, making their synthesis from waste not only environmentally responsible but also economically promising (Hernández-Saravia & Carmona, 2023). Recent studies have emphasized the dual benefit of this transformation: mitigating ecological burdens while creating high-value products. Mining tailings and electronic waste can serve as rich sources of metals and metalloids,

which, when processed through techniques such as green biosynthesis or hydrothermal treatment, yield functional nanomaterials with broad industrial utility. For instance, Hernández-Saravia and Carmona documented the successful conversion of mining and e-waste into nanomaterials for use in sensors and water purification systems, underscoring both the environmental and technological significance of the approach (Hernández-Saravia & Carmona, 2023). Biogenic synthesis has emerged as a particularly promising strategy, leveraging microbial and plant-based systems to produce metal nanoparticles from mining waste. This not only reduces reliance on harsh chemicals but also aligns with low-carbon and green chemistry principles (Wong-Pinto et al., 2020). In parallel, other studies have demonstrated the feasibility of utilizing mining tailings for producing engineered nanoparticles, enhancing environmental remediation capacity while contributing to economic resilience in mining regions (Singh et al., 2025). Importantly, the economic potential of such valorization strategies is non-trivial. The transformation of low-value waste streams into high-performance nanomaterials introduces new revenue streams and supports job creation in underdeveloped or post-mining economies (Beisebayeva & Zhantikev, 2026). This aligns with broader global goals of sustainable resource management and innovation-driven green transitions. Ultimately, transforming mining waste into nanomaterials represents a compelling opportunity to synergize environmental stewardship with technological advancement. As research in this area accelerates, interdisciplinary innovation across materials science, environmental engineering, and industrial ecology will be critical in scaling these solutions for global impact.

The transformation of mining waste into nanoparticles

The transformation of mining waste into nanoparticles has emerged as a promising strategy that addresses both environmental remediation and the growing demand for sustainable nanomaterials. Various methods, ranging from chemical to biological and physicochemical approaches, are being adopted to recover valuable elements and convert

them into functional nanostructures. One of the most used techniques is chemical reduction, where metal ions extracted from mine tailings or acid mine drainage are reduced into nanoparticles using reducing agents such as sodium borohydride or hydrogen peroxide. This method is efficient, relatively simple, and cost-effective for synthesizing metals like silver, copper, and iron nanoparticles (Panayotova & Mirdzveli, 2023). Hydrothermal synthesis is another highly adaptable method, where reactions take place in aqueous media under high temperatures and pressures inside a sealed autoclave. Iron ore tailings, for instance, have been used to synthesize magnetite nanoparticles through hydrothermal processing, resulting in particles with controlled morphology and magnetic properties (Kumar et al., 2015). A variation of this technique, known as solvothermal synthesis, utilizes organic solvents instead of water, offering better solubility control and more precise nanoparticle characteristics. Solvothermal methods are particularly useful when extracting metals from organic-rich mining residues (Hernández-Saravia & Carmona, 2023). Electrochemical methods offer another route for converting mining waste into nanoparticles. In such systems, metal ions from leachates or mining wastewater are reduced and deposited on electrodes, forming nanoparticles. These systems can be tuned for selectivity and are often integrated into wastewater treatment schemes (Noman et al., 2022). Another advanced method is microemulsion synthesis, where nanoscale droplets in oil-water mixtures serve as confined reactors, allowing controlled growth of nanoparticles. While less common in mining waste applications, microemulsion systems provide excellent control over size and dispersion, particularly for multi-metallic or alloy nanoparticles (Abdelbasir et al., 2020). Sol-gel synthesis offers significant promise for converting silicate-rich mining waste into oxide nanoparticles. This method involves the hydrolysis and condensation of metal alkoxides or salts into a gel, which upon drying and calcination yields crystalline nanostructures. Mining and metallurgical wastes rich in aluminium or silicon are ideal feedstocks for this approach (Beisebayeva & Zhantikeev, 2026). The resulting nanomaterials find applications in construction, catalysis, and environmental technologies. Together, these techniques showcase a multifaceted approach to waste valorization, enabling sustainable resource recovery while generating high-value nanomaterials. The choice of method depends on waste composition, desired nanoparticle characteristics, and potential end-use applications. As global industries increasingly prioritize circular economy practices, these conversion technologies will play a pivotal role in linking waste management with advanced material production.

Applications of Nanomaterials

The integration of nanoparticles into diverse industrial sectors has revolutionized the material science landscape

by enabling enhanced functionality, reduced material consumption, and new capabilities across biomedical, environmental, agricultural, construction, and energy domains. Due to their nanoscale dimensions and high surface-area-to-volume ratios, nanoparticles exhibit unique physical, chemical, and biological properties that are increasingly being utilized for specific functional outcomes (Stark et al. 2015). In the biomedical field, nanoparticles have significantly improved drug delivery systems by enabling targeted delivery, controlled release, and enhanced solubility of poorly water-soluble drugs. Organic and inorganic nanoparticles, such as liposomes, gold nanoparticles, and silica nanoparticles, are now commonly used in cancer therapy, diagnostics, and imaging (Khan et al., 2022). Similarly, silver nanoparticles, known for their antimicrobial activity, have been widely adopted in wound dressings, coatings for surgical tools, and personal care products (Verma & Maheshwari, 2019). The construction industry has benefited from the use of nanoparticles like nano-silica and nano-TiO₂, which improve mechanical strength, durability, and self-cleaning properties of cementitious materials. Nanoparticles also impart flame retardancy and corrosion resistance to coatings and composites used in infrastructure development (Mohajerani et al., 2019). In agriculture, nanoparticles enhance nutrient delivery and pest control while reducing chemical usage. Green-synthesized metal nanoparticles, often produced using microorganisms or plant extracts, offer biocompatibility and low toxicity, making them suitable for agrifood applications (Bahrulolum et al., 2021). These developments align well with the goals of sustainable farming and reduced agrochemical residues. The energy sector has adopted nanoparticles for improving the efficiency of photovoltaic cells, batteries, fuel cells, and hydrogen storage systems. Titanium dioxide (TiO₂), carbon nanotubes, and graphene-based nanoparticles are widely used in solar panels and supercapacitors due to their high electrical conductivity and photoactivity (Chakrabarty et al., 2022). Metal oxide nanoparticles have also found use in water-splitting and photocatalytic applications to promote clean energy solutions (Chavali & Nikolova, 2019). Moreover, in environmental applications, nanoparticles are employed for pollutant degradation, water treatment, and air purification. Their high reactivity and tunable surfaces allow for the adsorption or breakdown of heavy metals, dyes, and organic pollutants from contaminated media (Ealia & Saravanakumar, 2017). These wide-ranging applications are further supported by advancements in green synthesis techniques, which utilize plant extracts, microbes, and biomolecules to produce environmentally benign nanoparticles (Sharma & Tripathi, 2022). As industries increasingly adopt circular economy frameworks, nanoparticles synthesized from waste materials or using eco-friendly methods are poised to play a central role in next-generation technologies.

Economic Potential of Converting Mining Waste into

Nanoparticles

The conversion of mining waste into nanoparticles presents a unique intersection of environmental remediation and economic opportunity. Mining waste—often viewed as a costly liability due to its environmental hazards—can be transformed into a high-value resource through nanotechnology. The economic potential lies in both resource recovery and the production of commercially viable nanomaterials that serve diverse sectors such as medicine, energy, agriculture, and electronics (Wong-Pinto et al. 2020). Several studies highlight the direct economic advantages of reprocessing tailings and slag to synthesize nanoparticles. According to Hernández-Saravia and Carmona (2023), the valorization of mining and electronic waste into functional nanomaterials can significantly offset waste management costs while generating new revenue streams from materials such as silver, copper, and iron oxide nanoparticles. These nanoparticles are increasingly used in catalysis, biomedical devices, and environmental remediation, contributing to the global nanotechnology market valued at over \$100 billion. In regions where mining constitutes a substantial portion of GDP, such as Chile, the potential for value recovery from waste is considerable. Wong-Pinto et al. (2020) argue that the bionanominating of metal-rich waste could reduce environmental liabilities and create biotechnology-based industries focused on sustainable nanoparticle production, thus contributing to national economic development. Moreover, Singh et al. (2025) emphasized that mining tailings represent a largely untapped resource for nanomaterial production. As countries shift toward circular economy models, the recovery of high-performance materials from mining waste supports industrial symbiosis and reduces reliance on virgin raw materials—both of which contribute to long-term economic resilience. From a techno-economic standpoint, Abdelbasir et al. (2020) and Noman et al. (2022) found that using biosynthesis and green chemistry to generate nanoparticles from waste not only reduces synthesis costs but also adds market value by aligning products with eco-certifications and sustainability criteria. This dual economic and environmental benefit supports scalable business models for nanoparticle-based product lines. Furthermore, a study by Yu et al. (2024) shows that mineral waste recycling can turn traditional waste management expenses into profits. By embedding nanotechnology into chemical engineering workflows, industries can derive secondary raw materials from tailings, contributing both to economic gain and material circularity. Even the biomedical field benefits. Banerjee et al. (2023) demonstrated that copper mine tailings can be processed into redox-active nanoparticles with potential pharmaceutical applications. The added value of such functional nanomaterials makes the cost of waste processing more than justifiable from an investment perspective. Collectively, these findings establish that the economic potential of converting mining

waste into nanoparticles is not merely theoretical. It is a practical, revenue-generating model that aligns with global sustainability goals while fostering industrial innovation.

Conclusions

The transformation of mining waste into nanomaterials presents a forward-looking approach that aligns with sustainability, innovation, and circular economy goals. By employing a variety of synthesis techniques, ranging from chemical to biological, valuable nanoparticles can be derived from tailings, sludge, and electronic scrap, converting environmental liabilities into functional assets. These nanomaterials find impactful applications in medicine, construction, agriculture, energy, and environmental remediation. Beyond environmental benefits, this conversion strategy also offers substantial economic opportunities by generating high-value products from waste, reducing raw material dependency, and creating new industrial pathways for resource recovery. As global industries embrace greener practices, this paradigm shift has the potential to redefine mining waste management while fostering interdisciplinary collaborations and scalable technologies. The future of mining, thus, lies not just in extraction but in transformation, where waste becomes a resource, and sustainability becomes a competitive advantage.

References

1. Hernández-Saravia, L. P., & Carmona, E. R. (2023). Sustainable use of mining and electronic waste for nanomaterial synthesis with technological applications: State of the art and future directions. *Environmental Technology Reviews*.
<https://doi.org/10.1080/17518253.2023.2260401>
2. Wong-Pinto, L., Menzies, A., & Ordóñez, J. I. (2020). Bionanominating: Biotechnological synthesis of metal nanoparticles from mining waste—Opportunity for sustainable management of mining environmental liabilities. *Applied Microbiology and Biotechnology*, 104(22), 9573–9585.
<https://link.springer.com/article/10.1007/s00253-020-10353-0>
3. Singh, S., Maurya, P., Karmakar, A., & Maurya, P. K. (2025). Mining tailings as a frontier for sustainable nanomaterials: Advancing circular economy and environmental innovation. *Environmental Geochemistry and Health*.
<https://link.springer.com/article/10.1007/s10653-025-02566-x>
4. Beisebayeva, A. S., & Zhantikeev, U. Y. (2026). Transformation of mining and metallurgical waste into functional materials: Overview of technologies and applications. *Journal of Mining and Metallurgy Research*,

3(2), 45–61.

<https://kims-imio.com/index.php/main/article/view/488>

5. Abdelbasir, S. M., McCourt, K. M., & Lee, C. M. (2020). Waste-derived nanoparticles: Synthesis approaches, environmental applications, and sustainability considerations. *Frontiers in Chemistry*, 8, 782. <https://www.frontiersin.org/articles/10.3389/fchem.2020.00782/full>

6. Beisebayeva, A. S., & Zhantikeev, U. Y. (2026). Transformation of mining and metallurgical waste into functional materials: Overview of technologies and applications. *Journal of Mining and Metallurgy Research*, 3(2), 45–61.

<https://kims-imio.com/index.php/main/article/view/488>

7. Hernández-Saravia, L. P., & Carmona, E. R. (2023). Sustainable use of mining and electronic waste for nanomaterial synthesis with technological applications: State of the art and future directions. *Environmental Technology Reviews*.

<https://doi.org/10.1080/17518253.2023.2260401>

8. Kumar, R., Sakthivel, R., Behura, R., & Mishra, B. K. (2015). Synthesis of magnetite nanoparticles from mineral waste. *Journal of Alloys and Compounds*, 645, S337–S341. <https://www.sciencedirect.com/science/article/pii/S0925838815013821>

9. Noman, E. A., Al-Gheethi, A., & Al-Sahari, M. (2022). Challenges and opportunities in the application of bioinspired engineered nanomaterials for the recovery of metal ions from mining industry wastewater. *Chemosphere*, 308, 136243.

<https://www.sciencedirect.com/science/article/pii/S0045653522026583>

10. Panayotova, M., & Mirdzveli, N. (2023). Useful nanoparticles from mining waste and acid mine drainage. *IOP Conference Series: Earth and Environmental Science*, 1254(1), 012063.

<https://iopscience.iop.org/article/10.1088/1755-1315/1254/1/012063/meta>

11. Bahrulolum, H., Nooraei, S., & Javanshir, N. (2021). Green synthesis of metal nanoparticles using microorganisms and their application in the agrifood sector. *Journal of Nanobiotechnology*, 19, Article 34. <https://link.springer.com/article/10.1186/s12951-021-00834-3>

12. Chakraborty, I., Hakeem, K. R., & Mohanta, Y. K. (2022). Greener nanomaterials and their diverse applications in the energy sector. *Clean Technologies and Environmental Policy*.

<https://link.springer.com/article/10.1007/s10098-022-02368-0>

13. Chavali, M. S., & Nikolova, M. P. (2019). Metal oxide nanoparticles and their applications in nanotechnology. *SN Applied Sciences*, 1, Article 607.

<https://link.springer.com/article/10.1007/S42452-019-0592-3>

14. Ealia, S. A. M., & Saravanakumar, M. P. (2017). A review on the classification, characterisation, synthesis of nanoparticles and their application. *Materials Science and Engineering*, 263(3), 032019.

<https://iopscience.iop.org/article/10.1088/1757-899x/263/3/032019/pdf>

15. Khan, Y., Sadia, H., Ali Shah, S. Z., Khan, M. N., & Shah, A. A. (2022). Classification, synthetic, and characterization approaches to nanoparticles, and their applications in various fields of nanotechnology: A review. *Catalysts*, 12(11), 1386.

<https://www.mdpi.com/2073-4344/12/11/1386>

16. Mohajerani, A., Burnett, L., Smith, J. V., Kurmus, H., & Milas, J. (2019). Nanoparticles in construction materials and other applications, and implications of nanoparticle use. *Materials*, 12(19), 3052.

<https://www.mdpi.com/1996-1944/12/19/3052>

17. Sharma, R., & Tripathi, A. (2022). Green synthesis of nanoparticles and its key applications in various sectors. *Materials Today: Proceedings*.

<https://www.sciencedirect.com/science/article/pii/S2214785321064324>

18. Verma, P., & Maheshwari, S. K. (2019). Applications of silver nanoparticles in diverse sectors. *ResearchGate Preprint*.

https://www.researchgate.net/publication/328872315_Applications_of_Silver_nanoparticles_in_diverse_sectors

19. Stark, W. J., Stoessel, P. R., & Wohlleben, W. (2015). Industrial applications of nanoparticles. *Chemical Society Reviews*, 44(16), 5793–5805.

<https://pubs.rsc.org/en/content/articlehtml/2015/cs/c4cs00362d>

20. Abdelbasir, S. M., McCourt, K. M., & Lee, C. M. (2020). Waste-derived nanoparticles: Synthesis approaches, environmental applications, and sustainability considerations. *Frontiers in Chemistry*, 8, 782.

<https://www.frontiersin.org/articles/10.3389/fchem.2020.00782/full>

21. Banerjee, A., Ghosh, R., Adhikari, T., & Mukhopadhyay, S. (2023). Development of nanomedicine from copper mine tailing waste: A pavement towards circular economy with advanced redox nanotechnology. *Catalysts*, 13(2), 369. <https://www.mdpi.com/2073-4344/13/2/369>

22. Hernández-Saravia, L. P., & Carmona, E. R. (2023). Sustainable use of mining and electronic waste for nanomaterial synthesis with technological applications: State of the art and future directions. *Environmental Technology Reviews*.

<https://doi.org/10.1080/17518253.2023.2260401>

23. Noman, E. A., Al-Gheethi, A., & Al-Sahari, M. (2022). Challenges and opportunities in the application of bioinspired engineered nanomaterials for the recovery of metal ions from mining industry wastewater. *Chemosphere*, 308, 136243.

<https://www.sciencedirect.com/science/article/pii/S0045653522026583>

24. Singh, S., Maurya, P., Karmakar, A., & Maurya, P. K. (2025). Mining tailings as a frontier for sustainable nanomaterials: Advancing circular economy and environmental innovation. *Environmental Geochemistry*

and Health.

<https://link.springer.com/article/10.1007/s10653-025-02566-x>

25. Wong-Pinto, L., Menzies, A., & Ordóñez, J. I. (2020). Bionanominig: Biotechnological synthesis of metal nanoparticles from mining waste—Opportunity for sustainable management of mining environmental liabilities. *Applied Microbiology and Biotechnology*, 104(22), 9573–9585.

<https://link.springer.com/article/10.1007/s00253-020-10353-0>

26. Yu, H., Zahidi, I., Fai, C. M., Liang, D., & Madsen, D. Ø. (2024). Mineral waste recycling, sustainable chemical engineering, and circular economy. *Resources, Conservation & Recycling Advances*.

<https://www.sciencedirect.com/science/article/pii/S25901>



Opportunities and Challenges in Sea Bed Mining

Rutuja Dhengre-1, Pratik Godbole-1, Kaustubh Deshpande-1, Sanjeevani Jawadand-2, Kirtikumar Randive-1*

1-Post Graduate Department of Geology, RTM Nagpur University, Nagpur

2-Shri Mathuradas Mohota College of Science, Nagpur

Correspondence*: randivel01@yahoo.co.in

Abstract

The growing global demand for critical minerals essential to renewable energy systems, digital infrastructure, and electric mobility has intensified interest in seabed mining as an alternative to terrestrial extraction. This paper examines the geological potential, technological advancements, strategic value, and environmental implications of deep-sea mineral resource development. Regions such as the Clarion Clipperton Zone, Mid Atlantic Ridge, and Central Indian Ocean Basin are highlighted for their richness in polymetallic nodules, cobalt-rich crusts, and seafloor massive sulphides. The study explores recent innovations in autonomous underwater vehicles, robotic extractors, and geochemical mapping technologies that are transforming exploration and extraction practices. It also critically evaluates the ecological risks posed by sediment plumes, habitat loss, and biogeochemical disruption in fragile deep-sea ecosystems. Governance challenges, including regulatory gaps, weak enforcement under the International Seabed Authority, and lack of equitable stakeholder participation, are discussed in the context of the United Nations Convention on the Law of the Sea and global marine law. Emphasis is placed on the need for a precautionary, science-driven framework that aligns seabed mining practices with sustainable development goals. The paper concludes that while seabed mining holds transformative potential for critical mineral supply security, its viability depends on adaptive legal frameworks, transparent governance, and robust environmental safeguards.

Keywords: seabed mining, critical minerals, deep-sea ecosystems, marine governance, sustainable development

Introduction

Seabed mining involves extracting mineral resources from the ocean floor and has emerged as a potential solution to the growing global demand for critical metals like cobalt, nickel, copper, and rare earth elements. With terrestrial resources under pressure and facing sustainability issues, the deep-sea frontier is now seen as a significant source of

untapped minerals, particularly in polymetallic nodules, cobalt-rich crusts, and seafloor massive sulphides. These deposits hold promise to support green technologies, including electric vehicles and renewable energy systems (Kirsanov & Katyshev, 2024). However, the pursuit of these opportunities is shadowed by considerable challenges. Key among these are the environmental risks posed by deep-seabed mining, including biodiversity loss, disruption of benthic ecosystems, and sediment plume dispersal that could affect wider ocean processes (Levin et al.2020). The deep ocean is among the least understood ecosystems on Earth, which heightens the uncertainty surrounding potential long-term impacts (Miller et al.2017). Further complexity arises from governance and legal frameworks. The international community, primarily through the International Seabed Authority (ISA), continues to debate regulatory measures, environmental safeguards, and benefit-sharing mechanisms, especially in the "Area" beyond national jurisdiction (Thompson et al.2018). The challenge lies in balancing commercial interests, technological advancement, and environmental protection within a precautionary and science-based approach (Cuyvers et al.2018). Ultimately, while seabed mining presents a potential solution to resource scarcity, it also compels the global community to confront the ethical, ecological, and legal dilemmas of exploiting one of Earth's final frontiers.

Resource Potential in Seabed Mining

Seabed mining represents a significant frontier for future mineral resource exploitation, offering access to vast, untapped deposits critical for modern technologies and the clean energy transition. These deposits, ranging from polymetallic nodules and seafloor massive sulphides (SMS) to cobalt-rich ferromanganese crusts, are particularly abundant in deep-sea environments like the Clarion-Clipperton Zone, Mid-Atlantic Ridge, and Western Pacific (Petersen et al. 2016). The geological potential of these resources is immense. Polymetallic nodules, for instance, contain high concentrations of manganese, nickel, copper, and cobalt, minerals essential for battery technologies and

renewable energy infrastructure. Estimates suggest over a trillion tons of nodules exist across the Pacific abyssal plains (Glasby, 2002). Likewise, SMS deposits, typically found near hydrothermal vents, are rich in zinc, gold, and silver. Cobalt crusts, which accumulate over millions of years on seamounts, offer a potential alternative to terrestrial cobalt mining, which is often geopolitically and environmentally fraught (Sakellariadou et al.2022). Advanced exploration technologies, including autonomous underwater vehicles (AUVs) and high-resolution sonar mapping, are enhancing the ability to locate and assess these deposits. Recent surveys have significantly improved resource quantification, aiding in the development of mineral inventories for commercial assessment (Peukert et al.2017). Despite these prospects, assessments caution that the resource potential varies by deposit type and location. For example, the accessibility and grade of SMS deposits are often constrained by rugged terrain and limited spatial extent. Moreover, considerable scientific uncertainty remains around the full resource estimations due to limited sampling and the complex nature of deep-sea environments (Levin et al.2020). In the context of global resource demands, especially for rare earth elements and battery metals, seabed minerals could complement terrestrial supplies, reduce supply chain vulnerabilities, and enable more sustainable economic models, if exploited responsibly (Sterk & Stein, 2015).

Region / Zone	Deposit Type	Key Metals	Geological Features / Notes
Clarion-Clipperton Zone (CCZ)	Polymetallic Nodules Nickel,	Manganese, Copper, Cobalt	World's largest nodule field (~6 million km ²); significant interest from multiple contractors
Mid-Atlantic Ridge	Seafloor Massive Sulfides	Copper, Zinc, Gold, Silver	Active hydrothermal vent systems; high-grade but localized and geologically complex deposits
Central Indian Ocean Basin (CIOB)	Polymetallic Nodules	Manganese, Nickel, Copper, Cobalt	Rich nodule coverage; India has a pioneer area licensed for exploration
Cook Islands EEZ (South Pacific)	Cobalt-Rich Crusts	Cobalt, Rare Earth Elements (REE), Nickel	Thick crusts on seamounts; potentially world's largest cobalt crust resource
Mariana and Tonga Trenches (W. Pacific)	Seafloor Massive Sulfides	Copper, Gold, Silver	High geothermal activity; sulfide-rich hydrothermal systems at great depths

Peru Basin (Southeast Pacific)	Polymetallic Nodules	Manganese, Nickel, Copper	Studied as a secondary alternative to CCZ with promising but smaller-scale resource base
Northwest Pacific Seamounts (Japan area)	Cobalt-Rich Crusts	Cobalt, Platinum, REEs	Japan actively exploring in its EEZ; seamount chains offer crusts of high metallurgical value

Table 1: Showing potential hotspots for mineral resources

Technological Opportunities and Advancements in Seabed Mining

Seabed mining has rapidly transformed from a conceptual frontier into a tangible industrial venture, thanks to accelerating technological innovation. The development of deep-sea mining systems is now driven by the need for efficient, minimally invasive, and cost-effective operations capable of functioning in harsh subsea environments. Advances in remotely operated vehicles (ROVs), autonomous underwater vehicles (AUVs), high-resolution seafloor mapping, and robotic drilling systems have significantly enhanced the precision and viability of deep-sea exploration and extraction (Guo et al.2023). One key technological advancement lies in AUV-mounted multibeam sonar and hyperspectral imaging systems, which enable detailed geochemical mapping and real-time resource assessment. These tools are increasingly essential for locating polymetallic nodules, seafloor massive sulphides (SMS), and cobalt-rich crusts with high accuracy (Peukert et al.2017). Robotics also plays a critical role in both exploration and extraction. For instance, deep-sea robotic crawlers equipped with hydraulic cutters and suction modules are being designed for selective, minimal-impact harvesting of SMS deposits (Agarwala, 2023). Countries like China have demonstrated rapid technological progression in seabed mining systems, deploying integrated platforms that combine survey, sampling, and pilot mining capabilities in a single mission. This vertical integration offers both economic and strategic advantages (Agarwala, 2021). Similarly, international collaboration in engineering and marine sciences is fostering hybrid technologies that combine real-time data transmission, AI-based route optimization, and dynamic environmental monitoring. Despite these innovations, major engineering challenges remain. The durability of machinery under high pressure, sediment plume control, and real-time environmental impact monitoring are all still under development. However, recent reviews suggest that advances in geotechnical engineering and adaptive marine systems will likely overcome these barriers soon (Du et al.2024). Thus, the technological horizon for seabed mining is promising. With continued investment and interdisciplinary collaboration, these systems could

transform global resource supply chains while navigating the complex legal and environmental terrain of ocean sustainability.

Economic and Strategic Potential of Seabed Mining

Seabed mining holds considerable economic and strategic promise, particularly in the context of the global transition toward renewable energy, digital infrastructure, and geopolitical resource security. The ocean floor is abundant in critical metals such as cobalt, nickel, rare earth elements, and manganese, resources that underpin lithium-ion batteries, solar panels, and other low-carbon technologies. As terrestrial sources become constrained, the economic case for tapping into seabed minerals has intensified (Toro et al., 2020). From an economic standpoint, seabed mining is projected to influence global metal markets by diversifying supply and potentially stabilizing prices for high-demand materials. Technological progress is reducing operational costs and improving extraction efficiency, making commercial deep-sea mining more financially viable. Strategic nations, including China, are heavily investing in seabed mining to bolster self-sufficiency and secure supply chains for rare earths and battery metals (Kirsanov & Katyshev, 2024). The strategic dimension is equally important. Control over seabed resources, especially in Exclusive Economic Zones (EEZs) and areas beyond national jurisdiction, offers states the opportunity to reduce dependency on politically unstable or monopolistic suppliers. Seabed mining could enable resource diversification and geopolitical leverage in critical mineral diplomacy (Rozemeijer & van den Burg, 2022). Economically, countries with jurisdiction over rich seabed zones, such as the Cook Islands, Norway, and Japan, stand to benefit from royalties, infrastructure development, and international investment. A key recommendation is for nations to integrate seabed mining within a “blue economy” strategy that maximizes socio-economic gains while upholding marine environmental integrity (Sakellariadou et al., 2022). While environmental concerns remain a barrier, studies suggest that the economic potential of polymetallic nodules in particular, owing to their widespread distribution and high metal content, makes them the most viable starting point for commercial operations (Cunningham, 2024).

Environmental and Ecological Challenges of Seabed Mining

The advancement of seabed mining raises profound environmental and ecological concerns, particularly due to the fragile and largely unexplored nature of deep-sea ecosystems. One of the principal challenges is the irreversible destruction of unique benthic habitats caused by mechanical disturbance during mineral extraction. These include polymetallic nodule fields and hydrothermal vent communities, many of which harbour endemic and slow-growing species that may not recover once disturbed (Cuyvers et al., 2018). Mining operations generate sediment plumes, clouds of fine particles stirred up from the seafloor, which can spread over large areas, smothering

habitats, disrupting filter-feeding organisms, and altering local biogeochemistry. Moreover, the noise, light, and vibrations introduced into the deep-sea environment can interfere with animal behaviour and ecosystem functioning (Miller et al., 2017). Ecological consequences extend beyond the mined area. Studies suggest that recovery may take centuries or longer, and in many cases, ecosystems may never return to their original state. In regions such as the Clarion-Clipperton Zone, pilot mining simulations have already shown significant long-term impacts, including reduced biodiversity and ecosystem function (Levin et al., 2020). Another concern is the potential for cascading effects throughout the oceanic food web, particularly as microbial processes and nutrient cycling are disrupted by deep-sea disturbances. These impacts remain poorly understood due to limited baseline ecological data, which hampers accurate impact assessments and restoration strategies (Thompson et al., 2018). Despite calls for robust environmental management, the governance framework, led by the International Seabed Authority (ISA), has been criticized for lacking sufficient ecological precaution, transparency, and enforceable standards (Howard et al., 2020).

Ultimately, while seabed mining may address critical mineral supply shortages, its environmental footprint poses existential risks to biodiversity and ocean health. Current scientific consensus urges a precautionary pause in commercial exploitation until knowledge gaps are resolved and meaningful safeguards are in place (Miller et al., 2021).

Legal and Governance Issues of Seabed Mining

The legal and governance landscape of seabed mining is centred on the United Nations Convention on the Law of the Sea (UNCLOS), which defines the deep seabed beyond national jurisdiction—the “Area”—as the “common heritage of mankind.” This legal principle requires that benefits from seabed mining be shared equitably and that the marine environment be protected from significant harm. The International Seabed Authority (ISA), established under UNCLOS, is the primary body mandated to regulate mineral activities in the Area (Thompson et al., 2018). One major governance challenge involves balancing industrial interests with environmental protection. Critics have highlighted that while the ISA has issued numerous exploration contracts, its progress on finalizing comprehensive exploitation regulations has been slow, raising concerns over transparency, environmental safeguards, and enforcement capacity (Levin et al., 2020; Ardron et al., 2018). Adaptive management—a regulatory approach that adjusts practices based on real-time data—is proposed as a solution to scientific uncertainty. However, legal scholars argue that embedding adaptive management into ISA procedures is hindered by institutional inertia and ambiguity in enforcement mechanisms (Craik, 2020). Furthermore, there are significant equity and participation issues. Voices from civil society, Indigenous groups, and small island nations remain underrepresented in ISA negotiations, even though these stakeholders may be

disproportionately affected by potential mining impacts. Public participation and stakeholder inclusivity have been called essential to ensure legitimacy and accountability in seabed governance (Ardron, Lily, & Jaeckel, 2023). As mining interest grows, governance must also extend to national waters. While some countries have enacted national legislation, global consistency is lacking. Comparative studies show variation in legal preparedness, with only a few nations (e.g., Norway, Japan) having robust frameworks for deep-sea mining within their Exclusive Economic Zones (Roux & Horsfield, 2020). In sum, the legal and governance issues of seabed mining remain a work in progress. The development of binding international regulations, equitable benefit-sharing mechanisms, and ecologically-informed decision-making are necessary to responsibly govern this emerging industry.

Risk Mitigation and Sustainable Development for Seabed Mining

As seabed mining moves closer to commercial reality, ensuring risk mitigation and alignment with sustainable development principles is critical. The inherent complexity of deep-sea ecosystems, along with scientific uncertainty, demands a precautionary approach. Effective risk mitigation must combine legal, technical, and ecological frameworks that can anticipate, monitor, and respond to adverse outcomes in real time (Leal Filho et al., 2021). A key methodology is the mitigation hierarchy; avoidance, minimization, restoration, and offsetting, applied to deep-sea ecosystems. This approach has been adapted from terrestrial conservation to address the unique vulnerabilities of deep benthic habitats. It emphasizes early-stage avoidance of ecologically sensitive zones, real-time impact monitoring, and scalable restoration methods (Howard et al., 2020). Formal risk assessment procedures, such as those outlined in ISO 31000, are being explored to create structured evaluations of technological, ecological, and socio-economic risks in seabed mining. These frameworks advocate for iterative risk identification, analysis, and mitigation planning to improve resilience in deep-sea operations (Cormier & Lonsdale, 2020). The International Seabed Authority (ISA) plays a pivotal governance role, and its regulatory design is increasingly tied to the UN's Sustainable Development Goals (SDGs), particularly SDG 14 (Life Below Water). Sustainable seabed mining must prioritize long-term marine ecosystem health, equitable benefit sharing, and transparent governance (Madureira et al., 2023). Restoration science is also advancing. Research is being conducted to understand how artificial substrates, seafloor reseedling, and microbial recolonization might help recover mined habitats. However, many experts caution that restoration in the deep ocean may not be ecologically or temporally feasible within human timescales (Cuvelier et al., 2018). Sustainable development in seabed mining ultimately requires integrated planning, international cooperation, and adaptive regulatory systems to ensure the deep sea is not sacrificed for short-term economic gain.

Summary and Conclusion

Seabed mining has rapidly evolved from a futuristic concept to a viable strategic option for sourcing critical minerals essential to the clean energy transition and digital infrastructure. The ocean floor, particularly in regions like the Clarion-Clipperton Zone, Mid-Atlantic Ridge, and Indian Ocean Basin, holds vast reserves of polymetallic nodules, cobalt-rich crusts, and seafloor massive sulphides, resources that are increasingly scarce on land. These deposits offer the potential to ease supply chain bottlenecks, reduce dependency on geopolitically sensitive terrestrial sources, and support the global shift toward decarbonization.

Recent technological advancements, such as autonomous underwater vehicles (AUVs), robotic mining crawlers, high-resolution geophysical mapping, and AI-integrated real-time monitoring, have made exploration and selective extraction of deep-sea minerals more precise and economically viable. Additionally, nations with exploration licenses and Exclusive Economic Zones (EEZs) rich in seabed resources stand to benefit economically and strategically, particularly in the context of resource security and blue economy initiatives. However, the opportunities are closely shadowed by formidable challenges. Chief among these are the environmental uncertainties and irreversible ecological impacts associated with disturbing deep-sea habitats, which are among the least understood ecosystems on Earth. Issues such as sediment plumes, biodiversity loss, and disruption to nutrient cycling pose long-term risks that are difficult to quantify or mitigate. Moreover, the existing legal and governance frameworks, particularly those under the International Seabed Authority (ISA), are still evolving and often lack clarity, enforceability, and stakeholder inclusivity. Given these complexities, a precautionary and science-based approach is essential. Risk mitigation strategies must be integrated with adaptive management, robust environmental baseline studies, and stakeholder-driven governance. Sustainable seabed mining is not merely a technical or economic endeavour, it is an ethical imperative requiring international cooperation, environmental stewardship, and equitable benefit-sharing. As the world looks seaward to secure its future mineral needs, it must do so responsibly, ensuring that one of Earth's final frontiers is not compromised for short-term gain. The path forward lies in balancing innovation with introspection, and progress with planetary integrity.

References

1. Agarwala, N. (2021). Advances by China in deep seabed mining and its security implications for India. *Australasian Journal of Maritime & Ocean Affairs*. <https://doi.org/10.1080/18366503.2021.1871810>
2. Agarwala, N. (2023). Using robotics to achieve ocean sustainability during the exploration phase of deep seabed mining. *Marine Technology Society Journal*, 57(1). PDF
3. Ardron, J. A., Ruhl, H. A., & Jones, D. O. B. (2018). Incorporating transparency into the governance of deep-

seabed mining in the Area beyond national jurisdiction. *Marine Policy*, 89, 58–66. Link

4. Ardron, J., Lily, H., & Jaeckel, A. (2023). Public participation in the governance of deep-seabed mining in the Area. In *Research Handbook on International Marine Environmental Law*. PDF

5. Cormier, R., & Lonsdale, J. (2020). Risk assessment for deep sea mining: An overview of risk. *Marine Policy*, 113, 103801. <https://www.sciencedirect.com/science/article/pii/S0308597X18306109>

6. Craik, N. (2020). Implementing adaptive management in deep seabed mining: Legal and institutional challenges. *Marine Policy*. Link

7. Cunningham, A. (2024). Assessing the feasibility of deep-seabed mining of polymetallic nodules. *Mineral Economics*. PDF

8. Cuvelier, D., Gollner, S., Jones, D. O. B., & Kaiser, S. (2018). Potential mitigation and restoration actions in ecosystems impacted by seabed mining. *Frontiers in Marine Science*, 5, 467. PDF

9. Cuyvers, L., Berry, W., Gjerde, K., Thiele, T., & Wilhelm, C. (2018). Deep seabed mining, a rising environmental challenge. IUCN. <https://www.academia.edu/download/112494084/2018-029-En.pdf>

10. Du, K., Xi, W., Huang, S., & Zhou, J. (2024). Deep-sea mineral resource mining: A historical review, developmental progress, and insights. *Mine Water and the Environment*. Link

11. Glasby, G. P. (2002). Deep seabed mining: Past failures and future prospects. *Marine Georesources & Geotechnology*, 20(2), 161–176. <https://doi.org/10.1080/03608860290051859>

12. Guo, X., Fan, N., Liu, Y., Liu, X., Wang, Z., & Xie, X. (2023). Deep seabed mining: Frontiers in engineering geology and environment. *Journal of Engineering Geology*. PDF

13. Howard, P., Parker, G., & Jenner, N. (2020). An assessment of the risks and impacts of seabed mining on marine ecosystems. PDF

14. Kirsanov, A. K., & Katyshev, P. V. (2024). Economic drivers of seabed mining. https://www.researchgate.net/profile/Aleksandr-Kirsanov-2/publication/378693255_Economic_drivers_of_seabed_mining/links/65e529f1adf2362b636a706b/Economic-drivers-of-seabed-mining.pdf

15. Leal Filho, W., Abubakar, I. R., Nunes, C., & Platje, J. (2021). Deep seabed mining: A note on some potentials and risks to the sustainable mineral extraction from the oceans. *Journal of Marine Science and Engineering*, 9(5), 521. <https://www.mdpi.com/2077-1312/9/5/521>

16. Levin, L. A., Amon, D. J., & Lily, H. (2020). Challenges to the sustainability of deep-seabed mining. *Nature*

Sustainability, 3, 784–794. <https://doi.org/10.1038/s41893-020-0558-x>

17. Madureira, P., Squires, D., & Ribeiro, L. P. (2023). The International Seabed Authority and the United Nations 2030 Agenda for Sustainable Development. *Energy Policy*, 178, 113743.

<https://www.sciencedirect.com/science/article/pii/S0301420723008772>

18. Miller, K. A., Brigden, K., Santillo, D., & Currie, D. (2021). Challenging the need for deep seabed mining from the perspective of metal demand, biodiversity, ecosystem services, and benefit sharing. *Frontiers in Marine Science*, 8, 706161.

<https://www.frontiersin.org/articles/10.3389/fmars.2021.706161/full>

19. Petersen, S., et al. (2016). News from the seabed – Geological characteristics and resource potential of deep-sea mineral resources. *Marine Policy*. Link

20. Petersen, S., Kräbichell, A., Augustin, N., & Jamieson, J. (2016). News from the seabed—Geological characteristics and resource potential of deep-sea mineral resources. *Marine Policy*, 70, 175–187.

<https://www.sciencedirect.com/science/article/pii/S0308597X16300732>

21. Peukert, A., Petersen, S., Greinert, J., & Charlot, F. (2017). Seabed mining. In *Submarine Geomorphology* (pp. 479–492). https://link.springer.com/chapter/10.1007/978-3-319-57852-1_24

22. Roux, S., & Horsfield, C. (2020). Review of national legislations applicable to seabed mineral resources exploitation. PDF

23. Rozemeijer, M. J. C., & van den Burg, S. W. K. (2022). Seabed mining. In *Blue Economy* (pp. 65–81). Taylor & Francis. PDF

24. Sakellariadou, F., Gonzalez, F. J., & Hein, J. R. (2022). Seabed mining and blue growth: Exploring the potential of marine mineral deposits as a sustainable source of rare earth elements. *Pure and Applied Chemistry*, 94(6), 607–628. <https://doi.org/10.1515/pac-2021-0325>

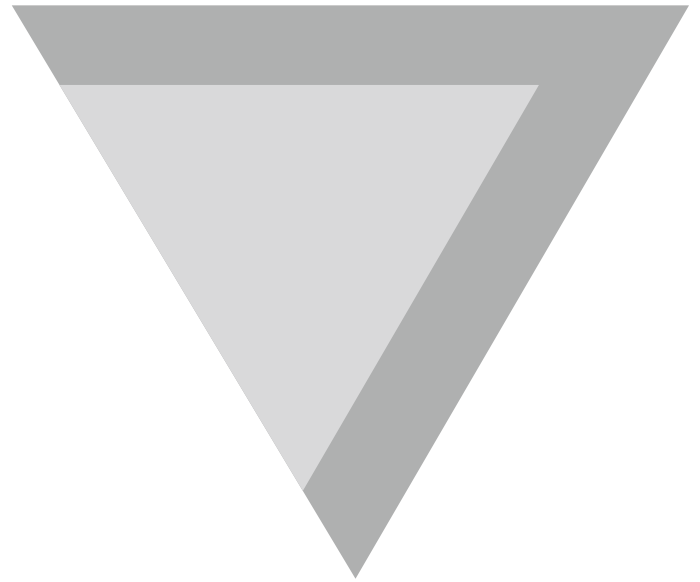
25. Sterk, R., & Stein, J. K. (2015). Seabed mineral resources: A review of current mineral resources and future developments.

https://www.researchgate.net/publication/363274057_Sea_bed_Mineral_Resources_A_Review_of_Current_Mineral_Resources_and_Future_Developments

26. Thompson, K. F., Miller, K. A., & Currie, D. (2018). Seabed mining and approaches to governance of the deep seabed. *Frontiers in Marine Science*, 5, 480.

<https://www.frontiersin.org/articles/10.3389/fmars.2018.0480/full>

27. Toro, N., Robles, P., & Jeldres, R. I. (2020). Seabed mineral resources: An alternative for the future of renewable energy. *Ocean & Coastal Management*, 193, 105233. Link



Sustainable Mining Techniques





Sustainable Mining Development with Best Management Practices

Dr. Gurdeep Singh

Advisor,
NORMI Research Foundation;
Founder Member,
Centre of Mining Environment,
ISM Dhanbad

The mineral industry in India is an important contributor to the Country's GDP and foreign trade and also a significant source of employment generation. The industry is distributed almost all across the country and has operations in some of the remotest areas, where it has also served as a sole source of infrastructure development.

Geological evidence suggests that India is richly endowed with mineral resources. Explanations have established over 20,000 known mineral deposits. India produces 89 minerals, out of which four are fuels, 11 metallic, 52 non-metallic, 3 atomic and 23 minor minerals. The mining leases occupy about 0.7 % million hectares, which is 0.21% of the total land mass of the Country. The Indian economy depends to a great extent on the value of the minerals produced, as these represent a major portion of raw materials for the nation's industrial activities. India is the second largest producer of coal in the world and one of the World's leading producers of bauxite, iron ore and zinc ore.

India's major mineral reserves lie under its richest forests and in the watersheds of its key rivers- these lands are also the homes of India's poorest people, its tribals. The three tribal dominated States of Jharkhand, Odisha and Chhattisgarh are the most productive mineral bearing States and account for about 70% of India's coal reserves, 80% of its high-grade iron ore, 60% of its bauxite and almost all its chromite reservoir. Forest cover in these States is far higher than the natural average of the top 50 mineral-producing districts in the country, almost half are tribal where average forest cover is 28% much more than the natural average of about 21% An estimated 1.66 lakh ha

of forest land has been diverted for mining in the country. A large part of the country's mineral bearing areas is in the grip of nexalism. 40% of the mineral- rich districts in the top six mineral producing States are affected by the naxal movement which is opposing the lopsided development that mining brings in.

Indiscriminate and unplanned mining causes irreversible damage and deterioration of natural resources. Mining activities affect surrounding i.e. air, water, soil, land, biological diversity etc. apart from the society. The environmental, social and economic impacts of mining activities may have short-term as well as long-term implications. Guidelines for taking necessary precautions before, during and after mining operations are laid down to ensure sustainable development. The role of mining in sustainable development is one issue that decision makers and resource managers have wrestled with for decades. Mining is one of those activities that really connect issues relating to people, development, and the environment. The negative impact of mining on health, land, water, air, plants and animals, and other aspects of society can be reduced by careful planning and implementation of mining activities. It is essential to strike a balance between mineral developments on the one hand and the restoration of the environment on the other.

Increasing globalization of the mining industry has led to changing public attitudes regarding the costs and benefits of mineral extraction and an increase in public pressure to minimize the environmental and social costs associated with mineral development. When the environmental impacts of mining operations are not properly managed and

mitigated, it is often too costly to restore mined lands to beneficial use once mineral deposits have been exhausted, leading to a net reduction in available land. It is therefore essential that the Indian minerals industry follows the principles of sustainable development by using methods and practices that minimize the release of contaminants to water, air and soil, preserve and restore lands for future use, and manage displaced populations.

Mining is a vital segment of the Indian economy. Appropriate systems have been put in place to ensure sustainable growth of the sector, which include formulation of procedures for scientific prospecting and mining and development of a mechanism of prior environmental and forest clearances for mining projects. Our endeavor is to protect the health and safety of mine workers and the surroundings, as well as to safeguard the interests of indigenous people through rehabilitation and resettlement packages. Efforts are also under way to mainstream the

artisanal and small-scale mining sector in order to promote equity in the mining industry. The issues of scientific closure and reclamation of the abandoned mine sites and the exhausting ones are being taken on top priority by various policy instruments. Environmental Clearance mechanism as per EIA Notification 2006 ensures sustainable mining addressing environmental, social and economic aspects before, during and closure phases of mining. Sustainable Development Framework (SDF) as formulated under the Natural Mineral Policy is in place to promote sustainable mining.

VISION 2047 by Ministry of Mines / Government of India envisages comprehensive sustainable mining with particular emphasis on clean mining technologies coupled with Decarbonization and climate change action plans. A few case studies of best practices are highlighted in moving forward towards sustainable mining.



Analysis of Controlled Blast Ground Vibration Insight of Structure Natural Frequency

Naveen G C and Gopinath G

Scientist, Rock Blasting and Excavation Engineering Department
National Institute of Rock Mechanics, Bengaluru, Karnataka
rbeenirm@gmail.com

Abstract

Study was conducted to find the frequency range of blast induced dynamic seismic waves and its impact on the residential structures. Controlled surface blasting was carried out for accommodating various thermal power project components in varying geological condition. Blasting parameters were altered to collect various bands of particle velocity and its frequency. Analysis of blast induced ground vibration revealed that the frequency of monitored ground vibration was always larger than 14Hz in all the three directions. It was observed that the characteristic of blast vibrations changed abruptly due to change in rock strata and blasting competent rock resulted in higher frequencies particle velocity. The results in this paper presented perceived that the blasting by small diameter holes (38 and 45mm) produces high frequency blast vibration even for very low particle velocity and the frequencies generated does not fall in the natural frequency band of structure, which is much favorable condition for the residential structures.

Introduction

Blasting is a major operation in any excavation related activity with its known advantages like user friendly and economically viability, whereas the concern is that the influence of blast vibration involved in the activity. Recent advanced technologies and its adoption have provided a wide range of acceptable results and also managed the prime factors like ground vibration and its frequency range that influence the structure stability. In this paper, the results of ground vibration produced by controlled blasting carried out for construction of thermal power project are discussed and the range of frequency that was produced for various blasting parameters are analysed.

Natural frequency of structures

The structure develops inertia force when it is excited by dynamic loads like blasting seismic waves. At higher frequency range, individual components of the structure tends to vibrate where as in low frequency range, the vibration may cause movement of entire structure due to high shear stress. If a structure is subjected to vibration at its

natural frequency, the displacements at the structure will be maximum which leads to induced stress in the structure. Stiffer the building increases the natural frequency of the building and vise-versa. The natural frequency of any structure falls in the range of 4 to 16 Hz (Dowding et. al. 1980, Adhikari et. al. 1989, Pal Roy, 1998, P K Singh, 1998, Siskind et. al., 1996).

Buildings surrounding the study area was not same as each other and each structure had varying span, height and nature of construction which defined its natural frequency. The structures surrounding the study area were of one to three stories building of different construction material (Figure 1).



Figure 1. Blast location close to the structures.

Blasting parameters

Blasting was carried out to accommodate various components for construction of thermal power project. The maximum depth of strata excavated is 5m from the surface level. The geological strength parameters of the strata was studied and the strata in the excavation area falls in the range of Class-III with respect to geological strength index. Boulders were observed in the excavation area.

Jack hammer (38mm diameter) and crawler mounted drill machine (45mm diameter) was used to drill the holes to a maximum depth of 2.5m. Holes were charged with 25mm

and 40mm diameter cartridges respectively and initiated using non electric shock tube/nonel initiation system. The details of blast parameters are given in Table 1. The charge factor maintained was about 0.4 to 0.5kg/m³. The bench was formed by removing the toe for almost all the blast and the blasts carried out was systematically designed, executed and monitored. Whenever the blasting was carried out in close proximity to the structures, blasting mats were used for muffling the blasting area (Venkatesh H S et. al., 2013).

Table 1. Blasting parameters

Hole diameter	32/45mm
Hole depth	1.5/2.5m
Burden and spacing	0.7 to 1m/0.8 to 1.2m
Explosive	25mm/40mm cartridge
Initiation system	Non electric initiation system combination of 17/25/42ms, 250ms TLD
Charge factor	0.4-0.5kg/m ³
Muffling	Blasting rubber mats

Blast vibration

The blast induced ground vibrations were captured using standard tri-axial transducer (Minimate plus model from Instanetel). The main advantage of this instrument over the Micromate from Instanetel is the low frequency response range (2Hz). The ground vibration was captured at different distances from the blast location. Transducer was fixed in the ground as per the guidelines provided by International Society of Explosive Engineering (ISEE) (Anon, 1998). It was ensured that the geophone is buried inside the ground to get good coupling and with an intention that it shall capture actual ground vibration. Event trigger threshold limit was fixed at 0.51mm/s so that not to miss any small vibration data and the sensor check was performed prior to each blast data collection. For each blast, three peak particle velocity data and subsequent frequency was recorded in longitudinal, transverse and vertical directions. The monitored data was analysed and finally peak vector sum was derived for each blast.

Peak particle velocity and frequency analysis

Blast vibration involves ground vibration in the form of peak particle velocity. The main parameter that influence the peak particle velocity is frequency and is directly associated with the type of structure and its natural frequency (Singh P K et. al., 2010). It is universally know that the low frequency is the main root cause for structure instability and may lead to damage the structures. In more complex waveforms, the dominant frequency is not necessarily the frequency at the peak particle velocity but at the frequency at greater amplitude (Lighthill M J, 1980). In India, Director General Mines Safety (DGMS) has regulated the peak particle

velocity with reference to frequency and the type of structures which is subjected to ground vibration (Anon, 1997) and most of the international standards consider peak particle velocity and frequency as main parameters for fixing the blast induced standards (Anderson D A, 1993). According to the regulations, the structures are allowed to subject to higher peak particle velocity with higher frequency (Anon, 1998).

The primary goal of the study was to verify the blast vibrations frequency so that they are not falling in natural frequency band of surrounding structures. The natural frequency of the surrounding structures were estimated using its physical characteristics. The blast vibrations waveform was analyzed using advanced Blastware software. Each blast was analysed for peak particle velocity and its subsequent dominant frequency in all the three perpendicular directions (Figure 2a). From the analysis it was found that the recorded particle velocity was very less for the natural frequency band of structures (Figure 2b).

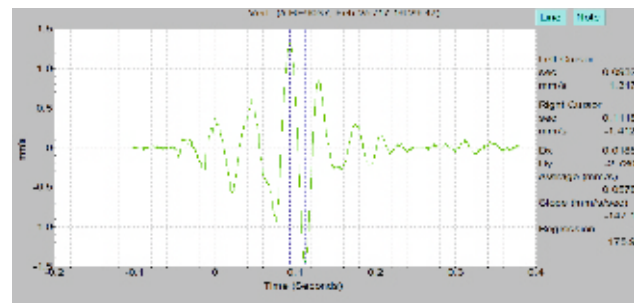


Figure 2 a. Analysis of blast vibration using advanced blastware software.

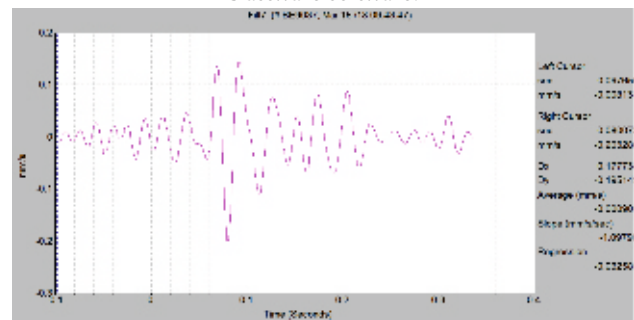


Figure 2 b. Analysis showing particle velocity and frequency band.

The recorded frequencies were in the range between 14Hz to 170Hz in all the longitudinal, transverse and vertical directions (Figure 3)

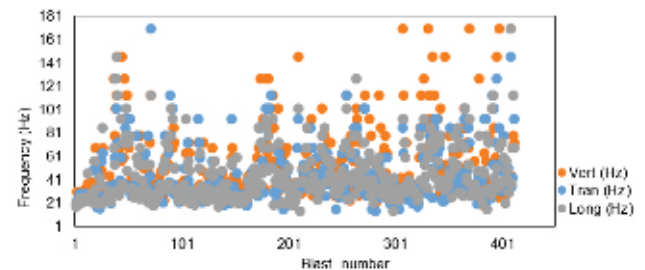


Figure 3. Plot showing frequencies recorded for different blast.

The ground vibration is directly linked to the charge quantity (Blair D P, 2014). In line with this Siskind et. al. (1980b) states that the damage levels are directly related to the largest single component peak particle velocity and its dominant frequency. From the study it was observed that even lowest peak particle velocity of 0.55mm/s was associated with high frequency of 170Hz and linear trend of increase in frequency for increased peak particle velocity was noticed (Figure 4).

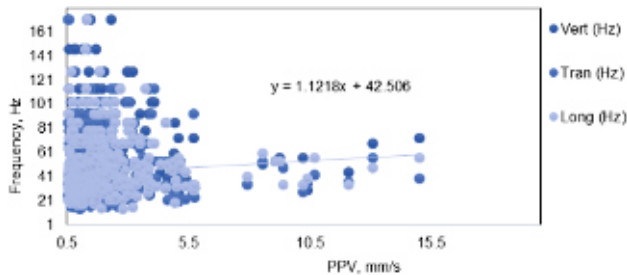


Figure 4 Plot of Peak Particle Velocity vs Frequency.

Higher frequency components in a signal will be attenuated more quickly than lower frequency components over a travelling distance (Blair, 1990). From the plot of distance vs frequency (Figure 5), it was observed that the frequency of vibration reduced with respect to increase in distance. Even though the matter is not a much concern in the present study due to higher frequency band when compared to natural frequency of the surrounding structure. The trend may influence on the stability of the structures at far distance where the frequency matches with the natural frequency of the structure for small peak particle velocity.

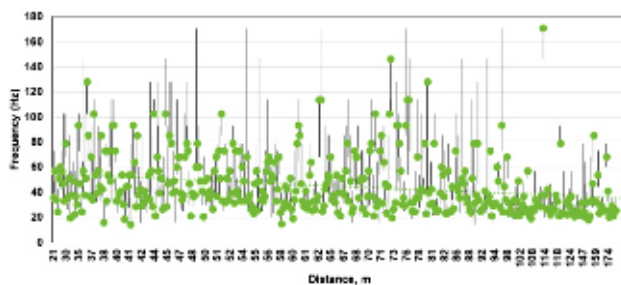


Figure 5. Plot showing monitoring distance and measured frequency.

Influence of geological conditions on frequency

The results of this study found that the frequency of the peak particle velocity and its frequency also has an influence on energy released by the explosive charge and the transmitting media (Blair D P, 2014). Siskind et al (1989) suggests that as distance from the shot increases, the particular influence of blast design is filtered out by transmission through the ground. Low frequency ground vibrations were recorded when blasting was carried out in disintegrated rock strata and higher range of frequency was recorded for higher particle velocity when blasting was carried out in competent rock (Figure 6) thereby proving

that damage from blasting competent rock is less when compared to blasting disintegrated rock strata. The characteristic frequencies of the ground will tend to dominate the waveform since they propagate most efficiently. It was also observed that when the monitoring stations were located in disintegrated strata, the resistance to travel of seismic waves generated low frequency ground vibrations. It was also observed that the distance is not always related to the ground vibration whereas geological structures/failure planes also influence the frequency of the ground vibration.

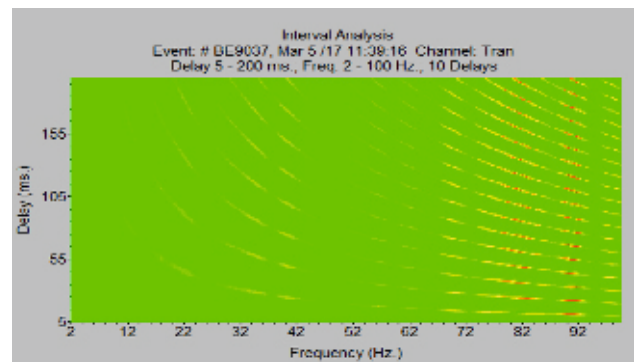


Figure 6 Frequency of ground vibration obtained when blasting in competent rock.

Conclusion

1. The findings of this study revealed that the frequency is mainly depended on the maximum charge per delay. Small quantity explosive detonated produced high frequency ground vibrations which was always greater than 14 Hz and not falls in the range of natural frequency of the structures.
2. The study also indicated that the blasting vibration changes numerously due to change in rock strata and also depends on direction of monitoring station. Higher frequency was recorded for higher particle velocity when blasting competent rock.
3. The general tendency of reduction in frequency with respect to increase in distance was observed. Very low particle velocity was recoded in lower frequency band which was not a concern in terms of structure stability.
4. Use of non-electric shock tube initiation have led to minimize the scattering effect of delay which is very much essential in avoiding the unexpected ground vibrations and is more effective means to control the damage of the structures.
5. The outcome of the analysis made way to continue with the followed technique since the measured data was safer with respect to the structure stability. Even though the test results found to be more appropriate, case studies shall be carried in similar condition as the results are site specific.

Acknowledgments

The authors would like to acknowledge Director, NIRM for giving opportunity for taking up the studies at DSTPP, Odisha. The authors also acknowledge the contribution of Mr. K G Gowtham in data collection. The authors convey thankful regards to NTPC officers and management for their kind support during field studies.

References

1. Dowding C H, 1996. Construction vibrations, Prentice Hall
2. Adhikari, G R., Singh R B and Gupta R N, 1989. Structure response to ground vibration due to blasting in opencast coal mines. Journal of Mines, Metal and Fuels, April, pp. 135-138.
3. Pal Roy P, 1998. Characteristics of ground vibrations and structure response to surface and underground blasting, Geotechnical and Geological Engineering, Vol. 16, pp. 151-166.
4. Singh P K, 1998. A study on ground vibrations due to Rock Blasting, Ph.D. Thesis, Technical university of Clausthal, Germany, Papierflieger, Clausthal-Zellerfeld.
5. Siskind D E, Stagg M S, Kopp J W and Dowding C H, 1980: Structure Response Produced by Ground Vibration from Surface Mine Blasting, U.S. Bureau of Mines, RI 8507.
6. Venkatesh, H S, Balachander, R, and Gopinath, G, 2013. Approach to urban excavation with special reference to metro rail, journal of visfotak – explosives safety & technology safety, Vol. No. 7, March 2013, PP 35-40.
7. Singh P K, Roy M P (2010) Damage to surface structures due to blast vibration. Int J Rock Mech Min Sci 47(6):949–961
8. Lighthill M J, 1980. An introduction to fourier analysis and generalized functions. Cambridge, England, Cambridge University Press.
9. Anon, 1997, "Damage of structures due to blast induced ground vibrations in the mining areas", DGMS (Tech)(S&T) Circular No. 7 of 1997 dated 29.08.1997.
10. Anderson D A, 1993. Blast monitoring: regulations, methods and control techniques, In: J.A. Hudson (ed.): Comprehensive Rock Engineering, Pergamon Press, Vol. 4, pp. 95-110.
11. Anon, 1998, ISEE, Blaster's Hand Book (1998), International Society of Explosives Engineers (ISEE). Blaster's handbook. 17th ed. Bainbridge, OH, USA: International Society of Explosives Engineers; 1998.
12. Siskind D E, Stagg M S, Kopp J W & Dowding C H, 1980b. Structure Response and Damage Produced by Ground Vibrations from Surface Mine Blasting. U.S. Bureau of Mines RI 8507.
13. Blair D P, 1990. Some problems associated with standard charge weight vibration scaling laws, Proceedings of the Third International Symposium on Rock Fragmentation by Blasting, Brisbane, Australia, 26-31 August.
14. Blair DP (2014) Blast vibration dependence on charge length, velocity of detonation and layered media. Int J Rock Mech Min Sci 65:29–39
15. Siskind D E, Crum S V, Otterness R E & Kopp J W, 1989. Comparative Study of Blasting Vibrations from Indiana Surface Coal Mines. U.S. Bureau of Mines, RI 9226.



Safe & Sustainable Use of Explosives

Dr G.K.Pradhan

Professor of Mining Engineering & Dean

Faculty of Engineering & Technology, AKS University, (Satna)

Abstract

Rock excavation is one of the oldest part of the human civilization. Having started with sharp stones to dig and kill the wild animals, with entry of iron, it attracted the attention of researchers to develop alternate method to break the rock. Then came the developments made in explosives and blasting through 'black powder-gunpowder-NGs-slurries and emulsion' route. This was supported by 'igniter sticks-safety fuse-detonators (ordinary & electric, delay or plain)-detonating fuse-nonel/shock tubes-electronic system of detonation'. Explosives being an essential consumable in excavations and mining, have wide use in Indian mines. There have been quantum jump in its manufacturing capacity and usage. During its manufacture-transport-storage and use we have to follow some of the most stringent and state-of-the-art Rules and Regulations, under Mines Act 1952 and Explosives Act 1884. In view of the rise in accidents in recent years an attempt has been made to present some of the unsafe acts and also measures needed to make the operations safest.

Introduction

Today, on an average 90% and more excavations use explosives and balance by non-explosive means. In India also the use of non-blasting practices are very much revealed when we go through temples and monuments built on or using rock. Bhushundi, a type of explosive, was used in the Mahabharata War. Shataghni referred to in Sundara Kanda of the Ramayana means cannon. These historical facts of the knowledge of explosives in ancient India negate the Chinese claims of its 9th-century discovery of dynamite. These were mostly explosives used in the wars. Ghosh(2022) reported about the contribution of Sir P.C.Ray in preparing chemical bombs and explosives for Indian freedom fighters.

Kautilya mentions gunpowder in his Arthashastra (2nd century BC). The evidence for early gunpowder use in India is based on historical texts, such as the "Rasaratnakara" by Bhoja in 9th century CE and other ancient Indian

manuscripts, which describe the use of explosive mixtures. According to Soni(...), the commencement of coal mining dates back to the year 1774 when H.G. Heatly, the British magistrate of Chhota Nagpur Nagpur, together with John Summer, applied for and obtained the privilege of mining coal in Panchet and Birbhum, 125 miles to the north-west of Calcutta. Heatly had six mines in operation in 1777, which produced 90 tons of coal. In case of non-coal, Soni(...) further stated that 'The writings of Manu, Yajnavalkya and Patanjali of the pre-Christian era refer to bronze and brass. Both Kautilya's Arthashastra and the earliest Indian brass of Taxila belonged to fourth century BCE, while the earliest 14C date of Zawar Mine is 430+100 BCE. The Arthashastra provides the earliest firm literary evidence for the production of metallic zinc on a regular basis in India, which mentions brass as arkuta and refers to burning of a rasa (metal) to produce an eye salve or 'zinc'.'

Indian Scenario of Explosive Making

From the history of mining, it can be concluded that we are having a rich past in mining. Presently in several minerals, we have significant presence globally. Today, India is net exporter of explosives and accessories with manufacturers like Solar Industries have a very significant presence in several developed mining nations. We could achieve this due to a very dedicated team of scientists and engineers attached to our research organisations. The value of explosives exported during 2023-2024 was Rs. 1745.61 Crores, and exported 19052 MT of Ammonium Nitrate.

Apart from regulating the manufacture-use and handling of explosives PESO and DGMS have also contributed to the development of site specific explosives and accessories. Indian Bureau of Mines also play a vital role in this area and in metalliferous mining sector through provisions of MCDR and other Rules. In the areas of explosives use in excavations, the trend is ever growing. Table I, presents explosives manufacturing trend as per PESO Annual Report of 2023-24.

Class of Explosives	2019-20	2020-21	2021-22	2022-23	2023-24
Class 1 – Gun Powder (MT)	606	462	473	695	639
Class 2 - Cartridges (MT)	5,19,111	5,38,557	6,01,384	6,37,725	7,04,191
Class 2 - SME (MT)	8,96,285	9,30,643	10,33,526	12,52,456	13,82,859
Class 2 ANFO (MT)	24,479	21,093	23,160	20,629	21,988
Class 3 Div-2 (CB + PETN) (MT)	10,598	11,103	14,110	17,420	22,062
Class 6 Div 1 – SF (Mill. Meters)	35	39	38	37	37
Class 6 Div 2 – DF (Mill. Meters)	754	818	868	1,310	1,500
Class 6 Div 3 Detonators (Mill. Nos)	1,177	1,088	1,042	1,041	976

*PETN- Penta Ervthritol Tetra Nitrate

Safety in Mining & Blasting

There has been considerable fall in number of accidents in Indian coal mines, which is presented in the Figures 1 & 2 for coal mines and Table I for Non-Coal mines. However, the aim of achieving Zero Accident gets upset with slightest deviation from SOP and provisions of the Rules and Technical Circulars issued by PESO and DGMS at regular intervals. While regulators are very much concerned for ensuring implementation of the rules, they have also updated the various safety norms and guidelines. The most significant step has been introduction of Risk Assessment and Safety Management Plans for various mining operations.

Some of the vital areas of unsafe acts in the manufacture, use, transport and storage of accessories, cartridge explosives and bulk explosives including ANFO and SME are stated below :

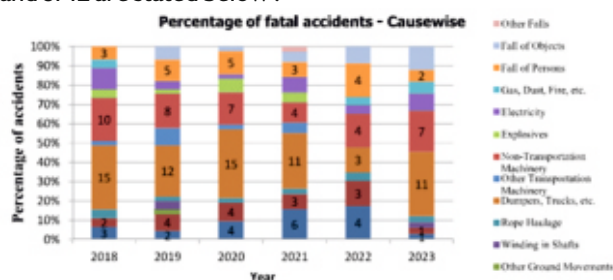


Figure 1 : Show cause-wise percentage distribution of all accidents respectively in coal mines during the year 2023.

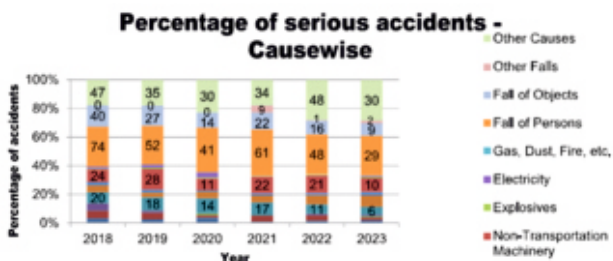


Figure 2 : Cause-wise percentage distribution of all serious accidents in coal mines during 2023.

Table I : Trend of accidents in Non-Coal Mines – Cause wise

Causes	No. of Fatal Accidents					
	2018	2019	2020	2021	2022	2023
Explosives	0	6	0	4	0	4
Total	46	45	40	33	38	24

Causes	No. of Serious Accidents					
	2018	2019	2020	2021	2022	2023
Explosives	1	0	1	0	0	0
Total	23	60	24	45	49	34

Safety in the use of explosives had been the main thrust area of manufacturers, users and regulators. In this regard several studies have been undertaken and the role of research institutions and educational institutions imparting mining education is laudable. Despite these efforts there has been a rise in fatal accidents in recent years.

Sustainable Mining

One vital feature of sustainable mining has been to be friendly with the communities living in and around the mines (SDG 11), maintaining ecological balance and support climate action (SDG 13),

Decent work and economic growth – leading to meet the requirement of raw materials for various vcore sector from mining (SDG 8), Industry, innovation and infrastructure (SDG 9), Responsible consumption and production (SDG 12), Climate action (SDG 13), and Partnerships for the goals (SDG 17).

In case of blasting also our aim has been to be innovative so that use of explosives, handling, storage and manufacturing become sustainable. In the recent years the following steps have been taken to make blasting operations safe and sustainable –

- (a) Use of state-of-the-art Bulk Emulsion explosives – efforts were made to totally use Indian make Bulk Delivery Units in Indian and overseas plants. This has been in line with our Make in India effort of our Honourable Prime Minister.
- (b) development and use of low density SME Explosives to reduce quantity of explosives used for blasting and also effective explosive energy use. Ex-Solar Industries had developed such formulations and these are in regular use.
- (c) Augmenting Ammonium Nitrate (prill grade) in India has been another area which had reduced imports.
- (d) Substitution for fuel in ANFO- ANFO which is widely used explosive globally has been gaining usage in majority of non-coal mines. Following provisions of AN Rules 2012, mines have streamlined its use. To ensure reduction in HSD in ANFO mix, research had helped in replacing as high as 35% of HSD with used Lubricants.

(d) Decarbonisation efforts in manufacturing units - through – Nitrous Oxide Abatement, Renewable Energy use, Fuel and Feedstock selection, Sourcing & Supply mix, Technological advancements in chemical feedstocks and Carbon offsetting.

2. Initiation : Use of shock tubes in almost all Indian mines - Use of Electronic delay detonators - Indian metal and coal mines have been very much accommodative to use Electronic Detonators through costly imports. The trend has been reversed and today we manufacture quality products costing around Rs.500/- per unit as compared with Rs.1800/- per unit when imported ten years back.

3. Quality Control : Use of special techniques to test various explosive composition. Mines like Utkal Alumina the single largest producer of Bauxite, has been using BULK ANALYSER QMR Blasting Analysis Instrument to test quality of SME (Figure 3).



Figure 3 : Shows the Bulk Analyser QMR Blasting Analysis set up

4. CO₂ Emission reduction & use of empty Plastic Bottles : Restricting the use of explosives with the help of air-gap techniques (Figure 4). According to a recent study published in India Today (June 23, 2025) India contributes 9.3 million tonnes, or 20 percent, to the 52.10 million tonnes of the annual global plastic waste emissions. Pradhan et al (2012, 2015) have reported about the successful use of empty PET Water bottles in blasting column to reduce explosive quantity as well as improving blast quality significantly economically. Pradhan et al (2015) had reported that one kg of explosive when reduced helps in the reduction of 0.19 kg of CO₂ emission. Figure 5, explains CO₂ emissions in an opencast mine (Orica).

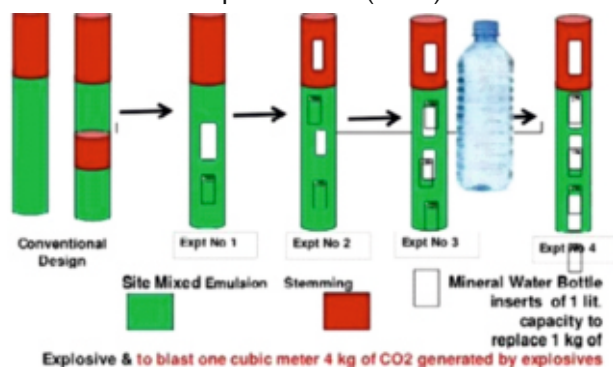


Figure 4: Use of empty discarded bottles in explosive column (ANFO and BULK)

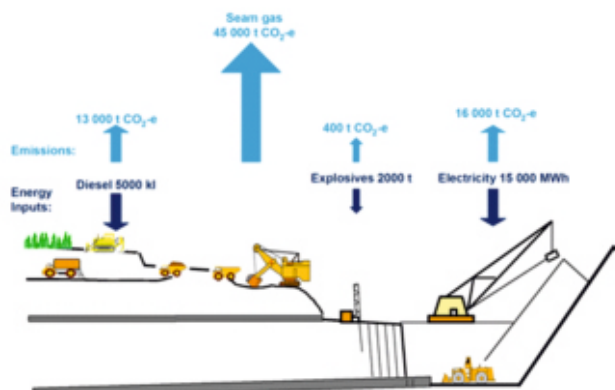


Figure 5 : Example of coal mine energy and emissions per million tonnes of coal ex-pit for a 7:1 stripping ratio dragline operation (Source : .Unearthing the Carbon Footprint- Australian Mining - March 2009)

5. Ammonium Nitrate Replacement - the widely/popularly used oxidizer with other chemicals. - Introducing new methods and systems of explosive use - Energetic materials containing concentrated hydrogen peroxide (OSM 'on-site-mixture' type energetic materials) are becoming increasingly popular. This contains in excess of 50 wt.% hydrogen peroxide (HP) and not containing toxic compounds, and therefore is environmentally friendly. They also perform better due to mechanical work and high VOD. (Polis, M et al (2024). Araos, and Onederra, (2017) have also reported about Nox free explosives. Their findings indicate that the mixtures with H₂O₂ can achieve a different VOD which depends on the size of the sensitising voids and more importantly, the mixtures behave as non-ideal explosive, similarly to ammonium nitrate-based explosives, but with the advantage of being a NO_x-free explosive.

6. Digitisation - Digital transformation has made a critical, enduring impact on mining operations in general and blasting in particular. This has provided users with tools to improve overall safety in manufacturing-handling-storage and use in addition to productivity. Today the online tracking system of explosives had helped in pilferage of explosives and accessories. By using ANN and AI, it has been very easy to design and evaluate blasting rounds. Singh (2004) had successfully demonstrated the use of ANN as an effective tool to blast evaluation, fly rock prediction etc in Indian mines. Extensive use of AI/ML tools, had helped in automation, data collection and evaluation to improve safety and skills etc.

Watoga Technologies, a Canadian mining-tech startup, through their flagship platform, RockHound, act as the digital brain of the modern mine — a centralized AI-driven system which optimizes blasting operations and the downstream processes. RockHound is a data-integrated, predictive analytics platform developed with deep domain expertise. Leveraging geology models, drill and blast data, explosive characteristics, and real-time feedback from downstream operations, RockHound enables data-

informed decision-making at every stage of the blasting process. It provides granular insight into in-situ rock conditions, prescribes optimized blast designs tailored to variable geology, and models the downstream impacts on material handling, comminution efficiency, and overall plant performance (Elboki 2025).

Conclusion

The entire globe and also India is all trying to reduce GHGs and to make the mining operation sustainable, Blasting being the widely adopted method of rock fragmentation is finding difficulty in getting replaced despite the various efforts due to its availability, and cost. In Indian context the time is proper to continue with our efforts to make our blasting operations safe and sustainable.

Acknowledgement

The views expressed are of the author and thanks are due to the management of AKS University for permission to present the paper at this prestigious event.

References

1. Araos, Miguel and Onederra, Italo (2017). Detonation characteristics of a NO_x-free mining explosive based on sensitised mixtures of low concentration hydrogen peroxide and fuel. *Central European Journal of Energetic Materials* 14 (4) 759-774.
<https://doi.org/10.22211/cejem/70835913>.
2. Bhattacharya, Asitesh. "Gunpowder and its Applications in Ancient India," in Brenda J. Buchanan ed. *Gunpowder, Explosives and the State: A Technological History* (Aldershot: Ashgate, 2006), pp. 42-50.
3. Elboki, T. (2025), Blasting into the future of mining, The Northern Miner Group's weekly newsletter, *Canadian Mining Journal*.
4. History (Aldershot: Ashgate, 2006), pp. 42-50. Ghosh, Rajarshi (2022), Contribution of Sir P.C. Ray in preparing chemical bombs and explosives for Indian freedom fighters, *Indian Journal of History of Science*, Volume 57, pages 49-51, <https://doi.org/10.1007/s43539-022-00029-1>.
5. India Today, June 23, 2025.
6. Orica (2009) : Unearthing the Carbon Footprint- Australian Mining - March 2009).
7. Polis, M et al (2024) Comprehensive study on impact of hydrogen peroxide decomposition on the crucial parameters of OSM-type energetic materials, *Scientific Reports* volume 14, Article number: 14093 (2024).
8. Pradhan G & Pradhan M, (2012), Explosive Energy Distribution in an Explosive Column Through use of Non-explosive Material-case Studies of Some Indian Mines, 10th International Symp. on Rock Fragmentation by Blasting, FRAGBLAST 10, New Delhi, Nov 24-29 pp 81-89.
9. Pradhan, G.K., Pradhan, M & Balakrishnan, V. (2015), Use of Discarded Water Bottles in Blasting-An Innovative Enviro-Friendly Technique, *Procc. Of Conference: International Journal of Chemical, Environmental & Biological Sciences (IJCEBS)*.
10. Raman Sundar D B, Satpathy R R, Satyanaryanan G V, Pradhan G K & Pradhan M (2013), Explosive Energy Distribution Through Placement of Low Explosive Air Gap -Case Study of an Indian Iron Ore Mine, 7th World Conference on Explosives & Blasting, Moscow, Sep 15-17, pp 22-29.
11. Singh T.N. (2004), Artificial neural network approach for prediction and control of ground vibrations in mines. *Mining Technology*. 2004; 113 (4): 251-256. doi:10.1179/037178404225006137
12. Singh. T.N. et al (2005), An intelligent approach to predict and control ground vibration in mines, *Geotechnical and Geological Engineering*, 23 (3) (2005), pp. 249-262.
13. Singh, T.N. et al (2014), Prediction of blast-induced flyrock in Indian limestone mines using neural networks, *Journal of Rock Mechanics and Geotechnical Engineering*, Volume 6, Issue 5, October 2014, Pages 447-454.

Reclamation Techniques in Mines: A Case Study Approach to Sustainable Land Recovery in India

Abhishek Bhadang, Priyesh kumar, K. M. Mulay

Corresponding Authors, B.Tech Final Year Student, Asst. & Assoc. Professor,

Department of Mining engineering, Rajiv Gandhi College of Engineering, Research and Technology, Chandrapur M.S. India.

Abstract:

Mining activities, especially surface mining, significantly impact land, water, air, and biodiversity. With increasing awareness of environmental degradation and sustainability, reclamation of mined-out land has become critical. This research paper examines the various reclamation techniques used in Indian mines, with specific case studies of Gouri Deep Opencast Mine and Saoner Mine No.I. Through a combination of technical and biological methods, these mines demonstrate the viability of restoring land for productive post-mining use. The study emphasizes integrated planning, community involvement, and sustainable technologies as vital components of effective reclamation.

Keywords: Reclamation, Surface Mining, Land Degradation, Ecological Restoration, India, Case Study.

1. Introduction India's rich mineral resources have driven extensive mining activities, particularly surface mining,

which contributes significantly to land degradation. The reclamation of mined-out land aims to restore ecological balance, ensure safety, and repurpose the land for agriculture, forestry, or recreational use. This paper explores reclamation techniques and presents case studies to highlight best practices and outcomes.

2. Methodology A descriptive and analytical approach was adopted using primary data from site visits and secondary sources such as government reports and academic publications. Case studies of Gouri Deep Opencast Mine and Saoner Mine No.I were selected to showcase reclamation strategies and outcomes.

3. Reclamation Techniques Reclamation is broadly divided into two categories:

3.1 Technical Methods: - Backfilling and grading of mine voids - Topsoil replacement and slope stabilization - Drainage system development - Infrastructure removal.



Technical Reclamation

3.2 Biological Methods : Revegetation with native plant species - Phytoremediation - Use of organic amendments (compost, biochar) - Development of green belts and eco-parks.



4. Case Studies

4.1 Gouri Deep Opencast Mine: Located in Chandrapur, Maharashtra, this mine has a lease area of 356.11 ha and operates with a capacity of 0.60 MTPA. Reclamation began during the operational phase and included: - Backfilling with overburden - Plantation of native species in dumps and voids - Use of technical and biological methods - Environmental monitoring and pollution control measures.



Backfilling and Dumping area of Gouri deep OC Mine

4.2 Saoner Mine No.1: This underground mine in Nagpur district has developed an Eco-Mine Tourism Park showcasing: - Land and water reclamation - Use of mine water for community use - Promotion of ecological awareness through mine tourism - RO plants and vermicomposting for sustainability

5. Results and Discussion : The case studies highlight that integrated reclamation efforts lead to successful ecological and social outcomes. The Gouri mine restored soil fertility and biodiversity, while the Saoner mine innovatively linked reclamation with community development. Key factors in success include early planning, multi-disciplinary coordination, and regular monitoring.

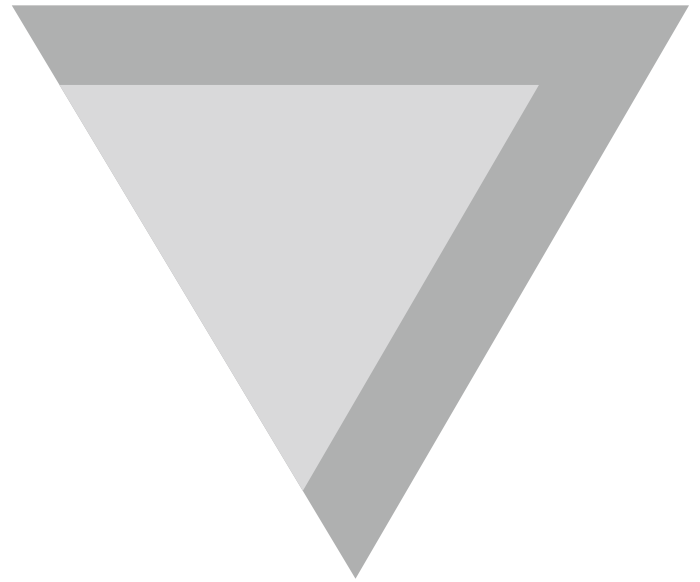
6. Conclusion : Reclamation is no longer a post-mining afterthought but an integral part of Mine planning. Indian mines have made significant progress through a mix of traditional and innovative techniques. Case studies reinforce the need for continuous improvement, stakeholder participation, and adherence to environmental standards for sustainable mining.

7. References:

1. Eco restoration of the Coal Mine Degraded Lands Dr. Subodh Kumar Maithi Publisher by springer Jan 2014
2. Eco-Restoration of Mine Land vol-I Vimal Chandra Pandey, Rupali Roy Chowdhury, Ritu Chaturvedi publisher Wiley 5 Jan 2003.
3. Bio-Geotechnologies for Mine Site Rehabilitation Dr M.N.V Prasad Elsevier Science 2001
4. A handbook on mine reclamation Published by the Indian Council of Forestry Research and Education (ICFRE) in 2020.
5. land restoration / reclamation monitoring of open cast coal mines of mahanadi coalfields ltd. based on satellite data for the year 2010, remote sensing cell geomatics division cmpdi, ranchi
6. land restoration / reclamation monitoring of open cast coal mines of southeastern coalfields limited based on satellite data remote sensing cell geomatics division cmpdi, ranchi
7. reclamation of coal mining operations: select issues and legislation-congressional research service.
8. ministry of steel- <http://www.steel.gov.in>, annual report 2022-23.
9. ministry of coal- <http://www.coal.gov.in>, annual report 2023-24.
10. western coalfields limited- <http://www.westerncoal.in>, initiative towards eco- mine tourism.
11. Sengupta, M. (2021). Environmental Impacts of Mining: Monitoring, Restoration, and Control (2nd ed.).
12. Reclamation of Disturbed Lands By Ian D.I. Foster 2006
13. Environmental Management in Mining Industry By G.A. Visser 2010
14. Mine Reclamation and Closure By A.B. Smith 2018
15. Mining and the Environment By John R. Chadwick 2015
16. Otto, J. M. (2009). Global Trends in Mine Reclamation and Closure Regulation. In Mining, Society, and a Sustainable World (pp. 251–288). Springer Berlin Heidelberg
17. United States Department of the Interior, Office of Surface Mining Reclamation and Enforcement (OSMRE).
18. Pan African Resources. (2024). Mine Site Rehabilitation: Importance, Practices
19. IBM, Ministry of Mines. Annual Environmental Reports.

Author Contributions: Abhishek Bhadang and their project group conducted field visits, compiled case data, and drafted the manuscript under guidance from Prof. Priyesh Kumar and Prof. K M Muly, Department of Mining engineering, RCERT Chandrapur M.S. India.

Conflict of Interest Statement: The authors declare no conflict of interest.



Critical Minerals



Unlocking the pathways through knowledge sharing for Critical Mineral investigation as exploration Geologist in nation building mission.

Satish Shenwai, Consultant

ABSTRACT

Investigation of Critical Mineral resources contribute to future energy needs, therefore sharing knowledge integrates geological inputs aimed to capture varying perspectives in untapping resources of required potential mineral deposits for the country.

This study consists, the preliminary Lithium exploration carried out at Zimbabwe by author; with the initial output, the shared analysis revealed the presence of Lithium and additionally important trace elements like Cassiterite, Tantalum and Rubidium in extractable range.

These findings contribute in developing exploration viewpoints for the suggested locations in Baster, Malkangiri & Mysore districts by author.

This paper largely represents many years of collective experience working on different mineral deposits with colleagues across India.

SUMMARY

M/s Avani Microlight Pvt. Ltd, Mumbai, has been intended to undertake a Mineral Resource potential study on the proposed Tin/Lithium blocks to develop Greenfield project and its processing in Nagpur, India. The Project located at Mashvingo (Bikita) in the Republic of Zimbabwe. Africa.

M/s Avani Microlight Pvt. Ltd, Mumbai, proposes to acquire the prospect license for the area which is located about 325 km southeast of its capital Harare and 80 km northeast of Masvingo, within the Masvingo greenstone belt. The author proposes to operate mining operations which covers 1640 hectares.

The area falls in the same Geological set up of the Bikita pegmatite deposit, a world-renowned large LCT (Lithium-Cesium-Tantalum) pegmatite-type rare metal deposit. It is a significant lithium-cesium-tantalum-beryllium production base in Zimbabwe and the world.

ANALYSIS RESULTS OF COLLECTED SAMPLES

Mashvingo (Bikita) Lithium Project			Assays % (oxides)						
S. No.	Brief description	Li	K	Na	Al	Fe	Cs	Ta	Rb
CP01	Peg. B, albite in artisanal miners pit	0.09	8.60	0.50	17.17	0.111	0.12	0.17	3.45
CP02	Peg. B, 12 x 22m across pink lepidolite	2.80	6.82	0.34	17.15	0.117	0.45	0.10	2.86
CP03	Peg. A, albite N of intersection point	0.04	0.87	8.01	14.87	0.230	0.61	0.04	0.19
CP04	Peg. A, spodumene	5.84	4.44	3.70	16.44	0.041	0.20	0.07	2.60
CP05	Peg. A, selective green muscovite & albite	0.12	3.30	6.32	16.3	0.260	0.33	x	0.63
CP06	Peg. A, qtz-fels-muscovite intergrowths	0.04	1.55	8.50	14.55	0.280	0.36	0.04	0.31
CP09	Peg A, qtz-fels-green muscovite intergrowths	4.96	0.74	0.49	16.70	0.039	0.84	0.10	5.60

Classification of lithium grade by percentage

S. No.	Lithium percentage	Grade/Remarks
1	0.00–0.99	Poor Grade
2	1.00–1.99	Low Grade
3	2.00–2.99	Medium Grade
4	3.00–4.00 and above	High/Highest Grade

GENWRAL ASPECTS

Lithium (Li) ore occurs naturally in various geological settings around the world. The most common lithium-bearing minerals found in lithium ores are spodumene, lepidolite, and petalite, which are typically found in igneous rocks, pegmatites, and sedimentary deposits. The distribution of lithium deposits is influenced by various factors, including geological processes, climate, and tectonic activity.

Pegmatites occur at many localities, The majority of these pegmatites do not contain lithium minerals, but they are mainly composed of quartz, feldspars, and muscovite, with accessory minerals that include tourmaline, beryl, apatite, garnet, zircon, Fe, Li, Mn, and Ca phosphates. Columbite group minerals and cassiterite are typically associated with zones of albitization.

1. Pegmatite Deposits: Pegmatites are coarse-grained igneous rocks that are enriched in rare elements, including lithium. Pegmatite deposits are one of the primary sources of lithium ore, particularly spodumene. Pegmatite deposits are found in various countries, including Australia, Canada, the United States Brazil & Zimbabwe.

2. Salt Brine Deposits: Lithium can also be found in underground brine deposits, which are formed by the evaporation of salty water in arid regions. These deposits are rich in lithium salts, such as lithium chloride, lithium carbonate, and lithium hydroxide. Salt brine deposits are primarily found in countries like Chile, Argentina, and Bolivia, where large salt flats, known as Salar's, are present.

3. Sedimentary Deposits: Lithium can also occur in sedimentary deposits, where it is typically associated with clay minerals. Lepidolite is a common lithium-bearing mineral found in some sedimentary deposits. Sedimentary lithium deposits are found in countries such as China, Russia, and the United States.

INDIAN ASPECT

As far as India's potential for this crustal natural wealth, country is blessed with good number of CRITICAL & RARE EARTH mineral occurrences, the probable potential areas are depicted for reference by author from his past working in these mineralised areas.

CASE-1. The author works on Metasedimentary Rocks from The Bastar-Malkangiri Pegmatite Belt (BMPB) in Parts of Chhattisgarh and Odisha, India during the year 1994-96 as an exploration team member for M/s Hamco Mining and Smelting Ltd, Mumbai.

Meta-Sedimentary Rocks and amphibolites host mineralized Rare Metal (Rare Minerals: Nb-Ta, Be and Li)- and Sn-bearing granite pegmatites.

BMPB extends over 80 km in a NW-SE direction from Dantewada in Bastar district of Chhattisgarh on the north-west to Salimi in Malkangiri district of Odisha on the south-east and passes through the villages of Metapal, Katekalyan, Tongpal, Govindpal, Mundval, Mundaguda and Dammoguda.

Unfortunately, these occurrences are not exploitable at present, either because of poor survey, or lack of detail exploration, or administrative problems, ultimately these vast resources lying unexplored.

CASE- 2. The studies were under taken by author during the exploration program in the year 2017-18, at Karya

Magnesite deposit for M/s Karnataka State Mineral Corporation Ltd, district Mysore, Karnataka, in a conventional method.

The detailed investigation requires to undertake around these obvious geological potential (OGP) blocks falling in Mysore district for presence of Rare Elements & Critical Minerals.

CASE-3. The author during the exploration programs found vast presence of Tourmaline bearing Pegmatites at different locations of Sausar Series Manganese ore belt associated with Manganese deposits.

Lithium ore, originally formed by primary sedimentary processes but modified by later metamorphism. During past research on pegmatites, nambulite is reported from the Woods mine, Australia (Coombs et al. 2009); the Tirodi Manganese mine in India.

Nambulite, a lithium- and sodium-bearing hydrous mangano-silicate, is formed by the reaction of a hydrothermal solution with the host mineral, Rhodonite may also serve as guides for lithium exploration.

The detailed investigation requires to undertake at these obvious geological potential (OGP) blocks falling in Sausar series areas in Nagpur district for presence of Rare Elements.

CONCLUSION- There will be a need for geologists, mineralogists, metallurgists, economists, and environmental experts to identify and apply the latest technological exploration methods in developing the potential mineral resources in mentioned areas.

ACKNOWLEDGEMENTS The author thanks Dr. Yogesh G. Kale, Controller of Mines (CZ), IBM, Nagpur and Shri. Gumna Ram, Deputy Controller of Mines I/C, Nagpur Regional Office, IBM, Nagpur, for inviting to present the manuscript.

The opinions in this paper are solely of the author and not of any organisation where he is currently working.

BIOGRAPHY The author possesses 30+ years of professional experience in Mineral Investigation and exploration Management including 15+ yrs as an entrepreneur in the field of in-depth Mineral Exploration consultancy and allied geological services.

Extensive experience in management of challenging projects for top Indian corporates independently in establishing their mineral base including Base metal, Rare Earth elements & Critical minerals across the country and outside.

The author is an alumnus of Nagpur University, Maharashtra, He is certified as RQP by Ministry of Mines, Government of India, currently he is working as freelance consulting Geologist with corporate organisations.

Thanks

Satish Shenwai.

Sustainable Lithium Supply through Secondary Extraction Technologies

Krutika Jangale-1, Pratik Godbole-1, Sanjeevani Jawadand-2, M.L. Dora-3 and Kirtikumar Randive-1*

1- Post Graduate Department of Geology, RTM Nagpur University, Nagpur

2- Shri Mathuradas Mohota College of Science, Nagpur

3- School of Environmental Sciences, Jawaharlal Nehru University, New Delhi

Correspondence*: randive101@yahoo.co.in

Abstract

As global demand for lithium surges due to its critical role in batteries and renewable energy storage, concerns are growing over the sustainability and environmental impact of conventional lithium mining. This paper explores secondary lithium extraction as a viable and eco-friendly alternative to primary sources, focusing on recovery from spent batteries, brine residues, mine tailings, and industrial waste. The study examines emerging technologies including hydrometallurgical processes, bioleaching, solvent extraction, and advanced membrane separation, evaluating them in terms of efficiency, cost, and environmental footprint. Secondary lithium extraction not only reduces pressure on primary lithium deposits but also minimizes the ecological damage associated with hard rock mining and brine evaporation. It further supports circular economy goals by extending the lifecycle of existing materials and reducing waste. Challenges such as impurity separation, process scalability, and regulatory gaps are discussed, along with recent innovations in selective recovery and automation. The paper advocates for integrating lithium recovery technologies into existing waste management systems and energy infrastructure, positioning secondary extraction as a key pathway toward sustainable lithium supply chains in the clean energy era.

Keywords: Lithium recovery, secondary lithium extraction, battery recycling, sustainable mining, circular economy, hydrometallurgy, lithium-ion batteries, e-waste management, resource efficiency, clean energy materials

Introduction

Lithium demand is growing due to global electrification trends which are driven largely by the rise of electric vehicles (EVs), smartphones, and other digital technologies. These innovations, which support carbon neutrality, make lithium indispensable for environmental sustainability and economic development. However, this rapid increase in demand exerts pressure on primary lithium sources, risking environmental degradation and overexploitation. This paper also brings attention to the parallel rise of e-waste, which is growing at a ~6% annual rate. Secondary

extraction, especially through recycling lithium from used batteries and electronics, is highlighted as a viable alternative to traditional mining. This method not only curtails pollution but also alleviates the strain on finite natural reserves (Baldé et al. 2024; Emilsson et al. 2021).

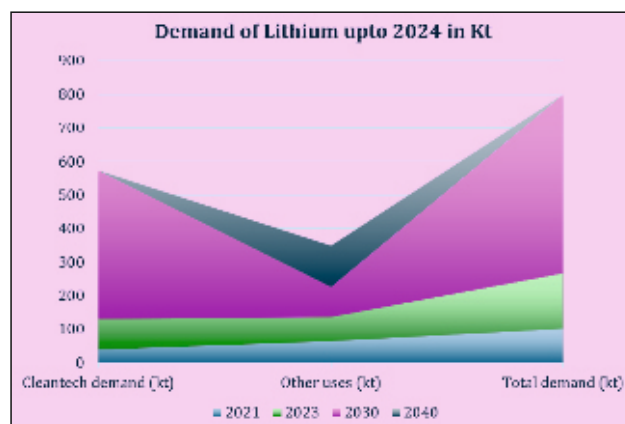


Fig: Showing Demand of Lithium in Kt (modified after IEA, 2024)

Applications of Lithium

Lithium, well known “white gold” due to its extensive utility in energy storage, especially in lithium-ion batteries. These batteries have central utility in power storage industries with a wide range of consumer electronics and are critical to EV revolutions (Agullo, 202). Besides batteries, lithium alloys with aluminum and magnesium enhance structural strength and are used in aerospace and automotive sectors. The medical industry also uses lithium as a mood stabilizer for bipolar disorder and other psychiatric conditions. A visual overview of lithium’s end-use applications underscores its cross-sector relevance from healthcare and communication to defense and transportation (Balram et al. 2024; Angino et al. 1974).

Extraction of Lithium from Primary Sources

Primary sources of lithium are derived from brines and naturally occurring minerals such as spodumene, lepidolite, petalite, zinnwaldite, and amblygonite. These prominent sources, typically processed through techniques like

calcination, roasting, chlorination, and pressure alkali leaching (Samoilov et al.2008; Song et al. 2019). In addition to this, continental brines found in salt flats of Chile, Argentina are significant contributors where lithium is extracted through solar evaporation and chemical precipitation (Choubey et al.2016). However, brine extraction for lithium is time-consuming and requires a vast amount of water, despite its cost-effective nature. This leads to concern about water wastage and ecosystem disruption (Agusdinata et al.2018). Each extraction methods requires to deal with efficiency, cost and environmental impact issues. For eg. acid roasting and chlorination methods can recover over 90% of lithium but involve high energy usage and pose risks like equipment corrosion, and toxic emissions hazards(Guo et al.2021). Although advancements have been made in extraction technologies, lithium mining from primary sources continues to raise environmental and social concerns, such as water scarcity issues for local populations and a threat to biodiversity, driving increased attention toward more sustainable secondary extraction methods.

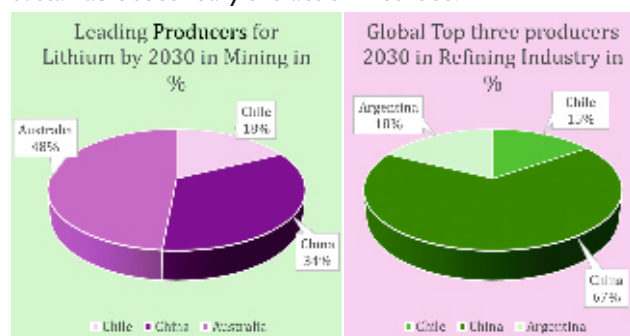


Fig: Showing top lithium producers in mining and refining sector by 2030 (modified after IEA, 2024)

Environmental impact	Primary Sources (Brines & Hard Rock)	Secondary Sources (Recycling & Waste Recovery)
Water consumption	Extremely high (e.g., ~500,000 gallons per ton from brines) (Agusdinata et al., 2018)	Low to moderate, depending on process (Swain, 2017)
Land degradation	Deforestation, soil erosion & open pit mining impacts (Choubey et al.2016)	Minimal land disturbance; mostly industrial setups
Biodiversity loss	Severe in fragile ecosystems like lithium triagle (Vikstrom et al.2013)	Negligible, no direct ecosystem encroachment
Toxic waste generated	Tailings and acid residues may contaminate water and soil (Choubey et al., 2016)	Positive job creation with low health/ environmental risk
Regulatory Concerns	Often weak enforcement, especially in developing regions	Easier to regulate in industrial/recycling zones
Sustainability Potential	Low, linear extraction depletes finite reserves	High, supports circular economy and resource efficiency (Swain, 2017)

Table 1: Environmental Impact of Primary and Secondary extraction of Lithium

Conclusion:

Lithium plays an important role to facilitate global electrification and digitalization, and its demand is accelerating with the growth of electric vehicles, consumer electronics, and energy storage technologies. While primary brine and hard-rock mineral sources like spodumene and lepidolite are important providers, their extraction is energy-intensive, ecologically taxing, and socially contentious, causing water scarcity, ecosystem disturbances, and wastes generation. These concerns have stimulated interest in secondary lithium sources like spent lithium-ion batteries, geothermal brines, industrial waste, and mine tailings. Secondary extraction technologies, including hydrometallurgical and pyrometallurgical processes, ion exchange, solvent extraction, and bioleaching, provide more sustainable and efficient recovery routes. Furthermore, industrial innovations from global players like Umicore, Toxco, and LithoRec demonstrate that lithium recycling can be commercially viable and environmentally responsible. Compared to traditional mining, secondary lithium extraction reduces land disturbance, emissions, and water usage, and hence is a vital solution to meet future lithium demand at non-prohibitive ecological expense

References:

- Angino, E. E., Thomas, H. E., & Dixon, W. (1974). Lithium in medicine and the environment. *Environmental Health Perspectives*, 9, 61–73. <https://doi.org/10.1289/ehp.740961>
- Agulló, E. (2022). The role of lithium in global electrification: Demand, supply, and sustainability implications. *Journal of Cleaner Production*, 357, 131906. <https://doi.org/10.1016/j.jclepro.2022.131906>
- Baldé, C. P., Forti, V., Gray, V., Kuehr, R., & Stegmann, P. (2024). The Global E-waste Monitor 2024: Quantities, flows and circular economy potential. United Nations University. <https://www.ewastemonitor.info/>
- Balram, A., Mehta, P., & Yadav, R. (2024). Strategic applications of lithium in sustainable industries: A review. *Global Sustainability Forum*, 12(1), 44–58. <https://doi.org/10.1016/j.gsf.2024.101868>
- Emilsson, E., & Dahllöf, L. (2021). Lithium battery supply chain and resource implications for electrification. Swedish Environmental Research Institute (IVL). <https://www.ivl.se>
- Agusdinata, D. B., Liu, W., Eakin, H., & Keck, A. (2018). Socio-environmental impacts of lithium mineral extraction: An analysis of the "lithium triangle" in South America. *Environmental Research Letters*, 13(12), 123001. <https://doi.org/10.1088/1748-9326/aae9b1>
- Bachmann, J., Schwarz, L., Ziemann, S., & Weil, M. (2022). Environmental and resource aspects of lithium recycling from electric vehicle batteries. *ACS Sustainable Chemistry & Engineering*, 10(12), 3877–3889. <https://doi.org/10.1021/acssuschemeng.1c08241>

8. Choubey, P. K., Jha, M. K., Singh, R. J., & Lee, J. C. (2016). Hydrometallurgical recovery of valuable metals from waste lithium-ion batteries: A review. *Minerals Engineering*, 89, 10–28. <https://doi.org/10.1016/j.mineng.2016.01.012>
9. Guo, B., Hou, H., Wei, L., Chen, S., & Huang, Y. (2021). Efficient extraction of lithium using chlorination roasting and leaching from spent lithium-ion batteries. *Minerals Engineering*, 163, 106789. <https://doi.org/10.1016/j.mineng.2020.106789>
10. Kolbel, T. (2023). Emerging opportunities for lithium recovery from geothermal and oilfield brines: A critical review. *Resources, Conservation and Recycling*, 190, 106857. <https://doi.org/10.1016/j.resconrec.2023.106857>
11. Samoilov, A. M., Babushkin, M. S., & Lobanov, A. N. (2008). Extraction of lithium from spodumene by roasting with Na_2CO_3 and leaching with water. *Hydrometallurgy*, 92(2–4), 148–154. <https://doi.org/10.1016/j.hydromet.2008.02.004>
12. Song, X., Liu, J., & Li, L. (2019). Extraction of lithium from petalite by chlorination roasting and water leaching. *Journal of Cleaner Production*, 220, 557–567. <https://doi.org/10.1016/j.jclepro.2019.01.324>
13. Yu, M. (2023). Circular economy perspectives in lithium resource recovery: Policies, practices, and environmental impact. *Journal of Environmental Management*, 331, 117349. <https://doi.org/10.1016/j.jenvman.2023.117349>
14. Bae, S., & Kim, H. (2021). Selective recovery of lithium from leachate using lithium-ion sieves derived from spinel-type manganese oxides. *Journal of Hazardous Materials*, 416, 125845. <https://doi.org/10.1016/j.jhazmat.2021.125845>
15. Guo, B. (2023). Ion-exchange technologies for selective lithium recovery: Mechanisms and industrial outlook. *Chemical Engineering Journal*, 457, 141150. <https://doi.org/10.1016/j.cej.2023.141150>
16. Heydarian, H., Zarei, M., & Behnam, S. (2018). Bioleaching of metals from lithium-ion battery using *Aspergillus niger*. *Waste and Biomass Valorization*, 9(7), 1239–1248. <https://doi.org/10.1007/s12649-017-9948-5>
17. Jayanthi, S., Karthik, S., & Rajalakshmi, N. (2023). Aluminum hydroxide as a recyclable lithium sorbent from industrial wastewater. *Journal of Environmental Management*, 330, 117125. <https://doi.org/10.1016/j.jenvman.2023.117125>
18. Kim, S., Lee, J., & Shin, W. (2018). Electrochemical recovery of lithium and simultaneous organic decomposition from battery recycling wastewater. *Separation and Purification Technology*, 197, 1–7. <https://doi.org/10.1016/j.seppur.2018.01.038>
19. Li, J., Zeng, X., & Chen, M. (2016). Eco-friendly recovery of lithium and cobalt from spent lithium-ion batteries using oxygen-free roasting and magnetic separation. *Waste Management*, 51, 227–235. <https://doi.org/10.1016/j.wasman.2016.03.004>
20. Meshram, P., Pandey, B. D., & Mankhand, T. R. (2014). Extraction of lithium from primary and secondary sources by pre-treatment, leaching and separation: A comprehensive review. *Hydrometallurgy*, 150, 192–208. <https://doi.org/10.1016/j.hydromet.2014.10.012>
21. Nayaka, G. P., & Manjanna, J. (2019). Extraction of lithium using organic acids and leaching agents. *Hydrometallurgy*, 188, 191–200. <https://doi.org/10.1016/j.hydromet.2019.05.016>
22. Sahu, K. K., & Devi, N. L. (2023). Green leaching of lithium from spent LIBs using lactic acid: A sustainable approach. *Journal of Cleaner Production*, 394, 136425. <https://doi.org/10.1016/j.jclepro.2023.136425>
23. Statista. (2024). Distribution of lithium-ion battery waste in India by application, 2021. <https://www.statista.com/statistics/india-lithium-battery-waste-by-application/>
24. Sun, X. (2024). Status report on India's LIB waste generation and treatment. *Environmental Monitoring and Assessment*, 196(5), 320.
25. Swain, B. (2017). Recovery and recycling of lithium: A review. *Separation and Purification Technology*, 172, 388–403. <https://doi.org/10.1016/j.seppur.2016.08.031>
26. Velazquez, T., Segura, M., & De La Cruz, J. (2019). Patented technologies for LIB recycling in Europe and North America. *Journal of Power Sources*, 435, 226774. <https://doi.org/10.1016/j.jpowsour.2019.226774>
27. Vikström, H., Davidsson, S., & Höök, M. (2013). Lithium availability and future production outlooks. *Resources Policy*, 38(1), 52–61. <https://doi.org/10.1016/j.resourpol.2012.09.002>
28. Wang, H., Sun, W., & Li, G. (2009). Recovery of lithium from spent lithium-ion batteries using HCl and organic acids. *Hydrometallurgy*, 95(3–4), 208–213. <https://doi.org/10.1016/j.hydromet.2008.06.010>
29. Wang, S., Zhang, L., & Zhou, J. (2017). Recovery of lithium from leach solutions using lithium-ion sieves. *Separation and Purification Technology*, 177, 254–263. <https://doi.org/10.1016/j.seppur.2016.12.034>
30. Xiao, Y., Tian, J., & Xu, J. (2017). Environmentally friendly roasting and separation process for spent LIBs. *Journal of Hazardous Materials*, 332, 101–110. <https://doi.org/10.1016/j.jhazmat.2017.03.007>
31. Zeng, X., Li, J., & Singh, N. (2014). Recycling of spent lithium-ion battery: A review on the chemical recovery process. *Waste Management*, 34(6), 1051–1063. <https://doi.org/10.1016/j.wasman.2013.12.002>

Critical Minerals for India's Defence Regime

Shantanu Prajapati, Pratik Godbole and Kirtikumar Randive

Post Graduate Department of Geology, RTM Nagpur University

Correspondence: prateek15godbole@gmail.com

India's aspirations for self-sufficiency in defence sector has increased due to recent escalations with neighbouring countries. This scenario demands for the uninterrupted availability of selected critical minerals which are vital for high-performance alloys, precision systems, advanced propulsion, and energy-dense storage technologies. However, current procurement patterns reveal a structural mismatch between domestic geological endowment and operational access to high-purity, defence-grade mineral inputs. This paper discusses India's current strategic posture on defence-critical minerals by mapping the disconnects between resource policy, mineral processing capabilities, and end-use defence sector demand. Through a targeted review of institutional efforts, ranging from mineral block auctions and KABIL's bilateral sourcing ventures to the inclusion of 17 minerals under high supply risk, the study identifies persistent gaps in refining infrastructure, inter-ministerial coordination, and long-

horizon stockpiling mechanisms. It shows how emerging threats from mineral nationalism, BRICS resource alignments, and unilateral export controls could constrain India's access to high-grade inputs required for aerospace composites, hypersonic platforms, and directed energy systems. The paper proposes the institutionalisation of a dedicated Defence Mineral Reserve Mechanism, integrated with forward contracts, domestic beneficiation pipelines, and a defence-sector mineral audit protocol. These measures are positioned as essential, not supplementary, to safeguarding India's technological sovereignty in an era of supply chain weaponisation and hybrid security competition.

Keywords: Defence-critical minerals, mineral security, strategic stockpiling, beneficiation, KABIL, supply chain resilience, mineral nationalism, BRICS alignment, technological sovereignty, high-performance alloys.



Critical Minerals Scenario of India in 2025: Geopolitical Risks, Domestic Challenges and the Path to Self-Reliance

Tejal Nirwan, Pratik Godbole, Sanjeevani Jawadand and Kirtikumar Randive

Post Graduate Department of Geology, RTM Nagpur University

Shri Mathuradas Mohota College of Science

Correspondence : prateek15godbole@gmail.com

Critical minerals (CMs) are essential for clean energy technologies, advanced defence systems, and digital infrastructure which has brought the strategic and economic significance of these resources to the forefront. Through an empirical assessment model adapted from the European Union and IEA methodologies, the Government of India identified 30 critical minerals based on two main axes, economic importance and supply risk, with 17 falling into the highest risk category. Nevertheless, despite hosting the fifth-largest reserves of rare earth elements (REEs), India's contribution to global production remains limited (~3.3%), primarily due to underutilized reserves, inadequate processing infrastructure, and dependence on imports for high-purity forms of cobalt, lithium, nickel, and graphite. One major concern for securing India's domestic reserves of several CMs lie in insurgency-affected regions, restricting accessibility and commercial exploitation; in spite of that, the Government of India has taken several measures to secure the CMs which are discussed in the present manuscript. Using correlation coefficient analyses from 2015 to 2024, the manuscript identifies fluctuating reserve data and mismatches between geological availability and economic access, further complicating long-term planning. Strategic responses including the ₹34,300 crore National Critical Mineral Mission (NCMM), trade partnerships (e.g., India-Australia CECA, India-Japan CEPA), and exploration efforts such as the IndiaAI Hackathon represent India's

multipronged approach to achieving mineral security. The manuscript also provides a comprehensive assessment of the global critical mineral landscape, with a sharp focus on India's position as of 2025. This study maps the production, reserve distribution, and geopolitical control of key CMs globally, highlighting India's reliance on mineral imports from China, DRC, and other politically volatile regions.

Another aspect which the present manuscript addresses is the evaluation of the environmental and regulatory challenges constraining sustainable CM development and recommends policy reforms such as streamlined mining clearances, investment in domestic processing, and the creation of Centres of Excellence for CM technologies. The role of critical minerals in achieving SDGs, particularly SDG 7 (Clean Energy), SDG 9 (Infrastructure), and SDG 13 (Climate Action), is quantified through sector-specific applications and mineral-to-SDG mapping. The study concludes with a strategic roadmap integrating geoscientific, policy, and technological interventions to reduce import dependency, diversify supply chains, and align critical mineral development with India's broader economic, environmental, and strategic goals.

Keywords: Critical Minerals, Rare Earth Elements, National Critical Mineral Mission, Clean Energy, Defence Technologies, Mineral Policy, Strategic Autonomy, Sustainable Development Goals



BALDOTA



20,15,963
Saplings
planted for
a greener
tomorrow



38,254 students across 101 schools benefited from better educational facilities and infrastructure.



14,509 people helped through eye screening and surgeries.



23 villages adopted to enable community progress.



56,250 people supported with essentials during COVID-19 pandemic.



10,350 people benefited through household toilet construction.



1,920 families empowered via active self-help groups.



2,832 differently-abled individuals supported with CSR activities.



4,37,352 young girls across 2,046 schools trained in self-defence.



6,661 individuals equipped with employable skills.



716 scholarships provided.



MOIL LTD.
Adding Strength to Steel



ADDING STRENGTH TO STEEL

Largest Manganese Ore Producer of the Country



#HarEkKaamDeshKeNaam

With Best Compliments From

PACIFIC EXPORTS

IRON ORE MINE OWNER

Village- Jhithi, Tehsil- Sihora, District- Jabalpur

Office Address- 4, Anand Vihar Colony, Madan Mohan Choubey Ward,
Bargawan, Katni (M.P.) 483501

Mobile No. - 9425156803



Taking the Community Along

towards a better tomorrow



Cares for the land and its people

RUNGTA SONS PVT. LTD.
MINING

Rungta House, Chaibasa, Jharkhand - 833201



M/s. SRI KUMARASWAMY MINERAL EXPORTS PRIVATE LIMITED



The mine has implemented Sustainable Development Framework in line with MCDR-2017 and awarded with 5-Star rating for past 6 Years from 2018-19 to 2023-24 by Ministry of Mines.



Mines Office :

M/s. SRI KUMARASWAMY MINERAL EXPORTS PVT LTD.
No.453, 14TH Ward, Smiore Colony, Near Fire Station,
Sandur(Tq), Ballari (Dist), Karnataka - 583 119
E-mail ID - riom@skmepl.co, Phone No : +91 6364516834
Website: www.skmepl.co

Corporate Office:

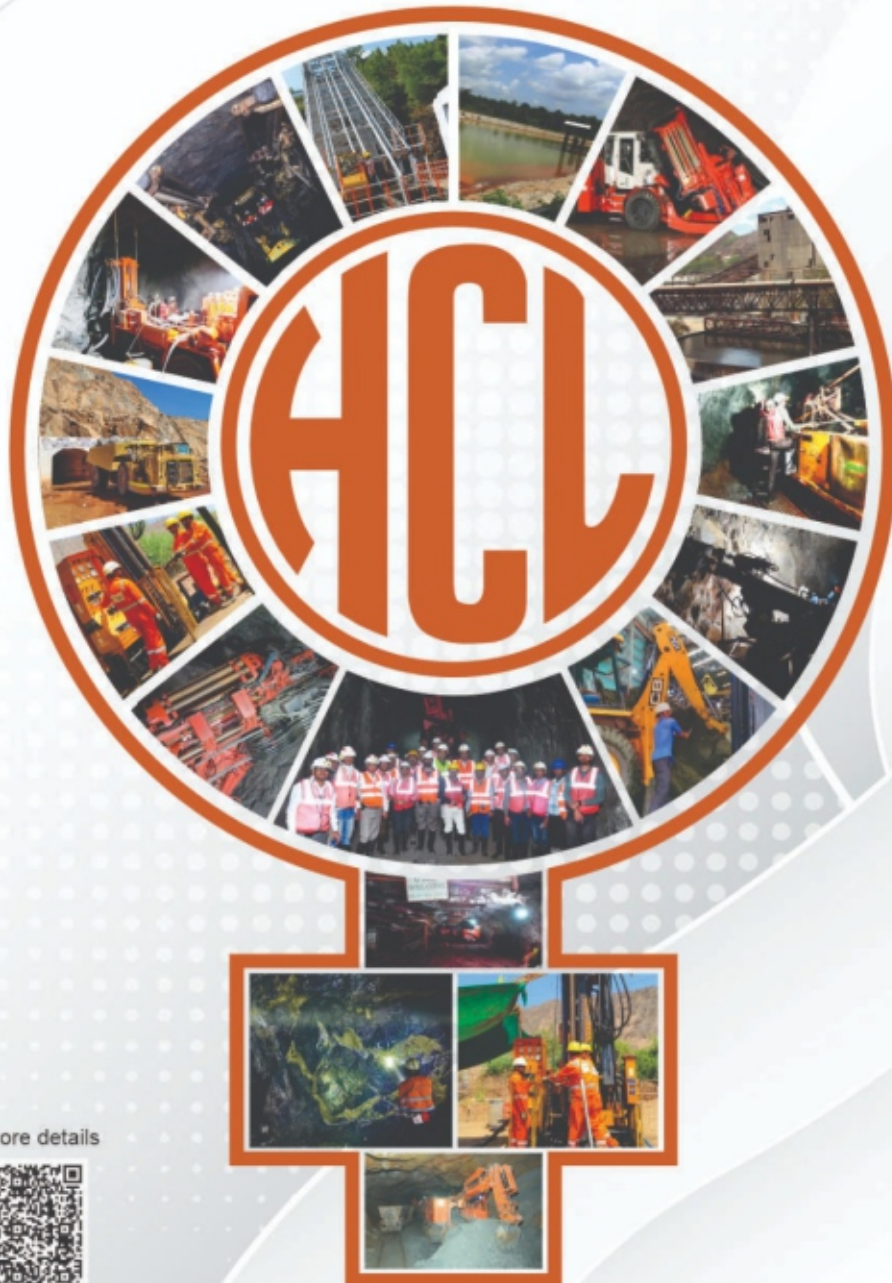
M/s. SRI KUMARASWAMY MINERAL EXPORTS PVT LTD.
No. 61, Cunningham Cross Road, Vasanthnagar.
Bangalore - 560 052

“We Mine with care”



हिन्दुस्तान कॉपर लिमिटेड
HINDUSTAN COPPER LIMITED
www.hindustancopper.com

The Copper Miner to the Nation



For more details



Scan the QR code



JKsuper

STRONG

CONCRETE SPECIAL

BUILD STRONG



एनएमडीसी



NMDC
Responsible Mining

New Look Soaring Aspirations Incredible Possibilities

Since our incorporation in 1958,
we have raised the bar in mining and
become India's largest iron ore producer.
Our philosophy as a Responsible Mining
Company has resulted in socio-economic
development of people around our projects.

NMDC Limited

(A Govt. of India Enterprise)

Regd. Office: Khanij Bhavan, 10-3-311/A,
Castle Hills, Masab Tank, Hyderabad - 500 028
CIN: L13100TG1958GOI001674

 nmdc.co.in

   
[/nmdclimited](https://www.facebook.com/nmdclimited)

NUVOCO®

Shaping a new world



Toll free: 1800 345 6666 | Whatsapp 'NUVOCO' to 98300 17272 | Choose from our range of 60+ products in: **CONCRETO** **DURAGUARD** **ZERO M**



MP BIRLA CEMENT
Cement se Ghar tak

*Inspired by Legacy
Driven by Quality*



Satna: Birla Vikas, Satna-485005 (MP) | Maihar: Village- Bharauli Post-Ithara, Maihar-485773 (MP)

Expert Advice: **1800 123 1117** | 98315 19191 | Follow us on:



ANAND MINING CORPORATION



At Anand Mining Corporation, we thank our valued partners and clients for being part of our journey. Your trust inspires us to deliver better every day.



INFOAMCKATNI@GMAIL.COM



07622-407888



WWW.ANANDMININGCORPORATION.COM



काँटि

www.mpbirlacement.com

परफेक्ट प्लस
नाही तर
काँक्रीट नाही



एम पी बिरला सिमेंट
परफेक्ट
प्लस

काँक्रीट स्पेशल

एक्सपर्ट एडवाइस: **1800 123 1117** ☎ **98315 19191**

Follow us on:    



MINING • STEEL • POWER



TOUCHING EVERY SPHERE OF LIFE

ERM GROUP COMPANIES

R. Praveen Chandra (Mine Owner)
Prakash Sponge Iron and Power Pvt. Ltd.
E. Ramamurthy Minerals and Metals Pvt. Ltd.
Benaka Minerals Trading Pvt. Ltd.
Codeland Infosolutions Pvt. Ltd.



www.ermgroup.in | www.turbosteel.in



*With
Best
Compliments*

FOMENTO RESOURCES

Corporate Office : Cidade de Goa, Vainguinim Beach, Goa, 403004
Website : www.fomento.com

NIRMALA MINERALS

*At Nirmala Minerals, we take pride in delivering excellence through responsible mining and superior quality minerals.
We sincerely thank our partners, clients, and community for their continued support.*



07622-407888



WWW.NIRMALAMINERALS.COM



NMKATNI@REDIFFMAIL.COM

HINDALCO INDUSTRIES LIMITED Hindalco Mining Group

Operates mechanized open cast Bauxite and Coal mines in the multiple districts and locations in the states of Jharkhand, Odisha, Chhattisgarh, Madhya Pradesh & Maharashtra



**We Manufacture Materials
That Make The World**

**“Greener
Stronger
Smarter”**

Dalmia cement

EIGHT DECADES OF STRENGTH, INNOVATION, AND EXPERTISE

Built on a legacy of strength and durability, Dalmia Cement offers a range of products for diverse construction needs; **Dalmia Cement**, trusted for stronger structures, and **Dalmia DSP RCF Expert ++**, designed for superior strength and lasting durability.



www.dalmiacement.com | 1800 2020 | [f](#) [@](#) [X](#) MyDalmiaCement

With Best Complements FROM



Chhotedongar Iron Ore Mine
of

M/s Jayaswal Neco Industries Limited

PRISM JOHNSON LIMITED



TILES THAT THINK BEYOND THE SURFACE.



Beyond looks and into advancement, tiles from H&R Johnson (India) are built to cool, shield, grip, and guide. Backed by 67 years of innovation, DSIR-recognised R&D, and modern factories, our 4500+ tiling innovations are designed to solve real-world challenges. From Radiation Shielding Tiles used in hospitals to Anti-static Tiles for static hazard-free areas, Solar Reflective Tiles that deflect heat to complete Swimming Pool Tiling solutions, Tactiles for safe navigation and many more, every product ensures safety, functionality, durability, and sustainability. With Johnson, you don't just get tiles, you get performance-driven value that protects, enhances, and endures.

☎ +91 84510 57484 | ☎ Toll Free No - 1800 210 7484 | ✉ tiles.customercare@prismjohnson.in

🌐 www.hrjohnsonindia.com | 📷 [hrjohnson_india](https://www.instagram.com/hrjohnson_india) | 📘 [HRJIndia](https://www.facebook.com/HRJIndia) | 📺 [hrjohnsonofficial](https://www.youtube.com/channel/UCrjohnsonofficial)

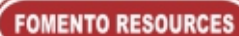
PLATINUM SPONSORS



GOLD SPONSORS



SILVER SPONSORS



SUPPORT SPONSORS





The Sandur Manganese & Iron Ores Limited



Felicitated as Seven Star Rated Mine - 2023-24 for Green Mining
by the Ministry of Mines, Indian Bureau of Mines

"Seven decades of Responsible Mining with commitment to sustainable development, safe and innovative practices, environmental stewardship and engaging with community.

We strive to safeguard social, economic and environmental well-being for current and future generations".

☎ 080-45473019

www.sandurgroup.com

✉ Investors@sandurgroup.com

REACHING DEEPER, AIMING HIGHER



AMPL is an end to
end service provider
to the mining industry.

OUR SERVICES

- Mine Development and Operation
- Mine Identification & Planning
- Assistance in R & R, Land Acquisition and obtaining other approvals
- Coal and Ash Logistics (Rail & Road)
- Crushing and Allied Services

OUR STRENGTH

- 30 Years of Operation in Private Mines and CIL.
- Mining Capability of 35 Million Cum.
- 12 operating projects (Coal & other minerals).
- Operation in 7 States.
- Pioneer in Surface Miner Operation.
- Crushing Capacity of 3 Million Tonnes per month.



MDO



LOGISTICS



ENERGY



Recipient of ET Bengal
Corporate Awards

AMPL Resources Pvt. Ltd.

(ISO 9001:2008 | ISO 14001:2004 | OHSAS 18001:2007)

info@ampl.in | www.ampl.in

WITH BEST COMPLIMENTS FROM



PACIFIC MINERALS PRIVATE LTD.

BAIHAR ROAD, BALAGHAT (M.P.) 481001
PHONE: 07632-248450
GRAM: STOUTNESS

REGD. OFFICE: 163, BALARAM DEY STREET, KOLKATA, WEST BENGAL PIN 700006