TRANSACTIONS

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Established 1906

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THE MINING, GEOLOGICAL AND METALLURGICAL INSTITUTE OF INDIA
Inaugurated 1906 - incorporated 1909 - as the Mining and Geological Institute of India, the word Metallurgical was included in the title in 1937.

Honorary Editor
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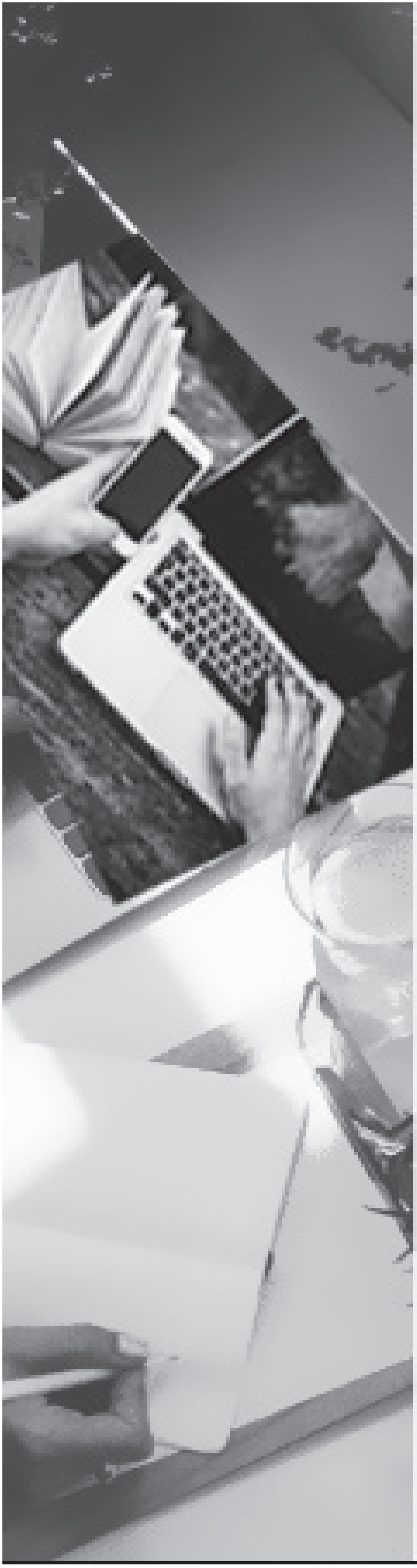

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THE MINING, GEOLOGICAL AND METALLURGICAL INSTITUTE OF INDIA
GN -38/4, Sector - V, Salt Lake, Kolkata - 700 091

EDITORIAL BOARD

PRESIDENTIAL ADDRESS FOR 118TH ANNUAL GENERAL MEETING OF MGMI AT BENGAL CHAMBER OF COMMERCE & INDUSTRY KOLKATA ON SATURDAY, 21ST SEPTEMBER 2024

Dr B Veera Reddy[1]

Dignitaries on the dais and off the dais, my friends of MGMI and Ladies & Gentlemen,

Good Afternoon!

I warmly welcome everyone to the 118th Annual General Meeting of MGMI, a century-old professional organization dedicated to the minerals and energy sectors. I sincerely appreciate your trust in me to serve as the President of the Institute for two consecutive terms. Thank you all for your continued support.

Minerals especially the energy minerals play a critical role in India's economy by contributing to country's industrial growth, infrastructure development, and energy production. We are rich in resources like coal, iron ore, bauxite, and oil and natural gas, which form the backbone of key industries such as steel, cement, and electricity generation. Energy minerals like coal and petroleum contribute significantly to meeting the country's energy demands, especially for power generation. The mining sector also generates employment, attracts foreign investment, and boosts export earnings. Overall, the exploitation of minerals and energy resources is essential for India's economic progress and self-reliance in energy.

The mineral sector in India faces several challenges and opportunities. A major challenge is its contribution to greenhouse gas (GHG) emissions, driven by energy-intensive mining and processing activities. This presents environmental concerns and pressure to meet global climate targets. Additional challenges in India's energy sector include energy security, as the country relies heavily on imports for oil and gas, and the moderate pace of renewable energy adoption. Despite ambitious targets, grid integration, storage solutions, and infrastructure upgrades are needed to fully harness the potential of renewable energy sources.

However, there are also opportunities for growth through the adoption of cleaner technologies and practices, such as renewable energy integration, carbon capture, and sustainable mining techniques. With the backing of the Ministry of Coal, Government of India, Coal India Limited is focusing on un-

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[1] President MGMI and Director (Technical), Coal India Limited
Presidential Address delivered on 21st September 2024 at the 118th Annual General Meeting at Williamson Magor Hall, 3rd Level, Bengal Chamber of Commerce & Industry, Royal Exchange Building, 6 N S Road, Kolkata

derground coal mining to optimize resource extraction, while ensuring safety and sustainable practices to fulfil India's increasing energy demands.

Government policies encouraging green initiatives, along with rising demand for minerals critical to renewable energy technologies, offer a pathway to reducing emissions while supporting economic growth in the sector.

India's discovery of critical minerals, such as lithium or rare earth elements, would significantly boost its economic and strategic standing. These minerals are vital for renewable energy technologies, electronics, and defence, reducing dependency on imports and supporting domestic industry and innovation.

MGMI has a solid foundation in technical expertise and extensive experience, which can play a pivotal role in ensuring the sustainability of the mineral energy sectors in India. For the foreseeable future, fossil fuels, particularly coal, will remain indispensable to the nation's energy needs, as no viable alternatives are poised to take their place over the next few decades. Despite this reality, the mineral and coal sectors often face criticism primarily for their environmental impact, land degradation and displacement rather than receiving the recognition they deserve for their vital contributions to energy security of the country. It is crucial to balance the narrative, acknowledging both their role in energy sustainability and addressing the environmental concerns proactively.

These sectors are evolving within a set of limitations, and it is crucial for MGMI to emphasize the ongoing efforts of stakeholders in overcoming these challenges. When addressing sustainability, MGMI must adopt a comprehensive approach, considering all aspects involved. A holistic perspective will ensure that growth is not just focused on immediate gains but also aligns with long-term environmental and economic stability, something that is deeply relevant to India's developmental goals.

Having dedicated forty years to the coal industry, I firmly believe that the sustainability of our country's energy sector hinges significantly on the coal sector's contributions. It is imperative for all of us present here to appreciate this reality and advocate for its importance. MGMI should develop comprehensive recommendations to bolster the growth of the mining sector, addressing critical areas such as environmental clearances, land acquisition, resettlement and rehabilitation, ecological restoration, social impact, and a just transition for affected communities.

Over the past two years, Kolkata, Delhi, Odisha, Nagpur, Hyderabad, Mumbai, Asansol and Dhanbad Branches of MGMI have seen significant revitalization, while many others remain relatively inactive. The more dynamic branches have been organizing a variety of events and initiatives. As a result, our membership has grown by more than 350 from 2050 to nearly 2,400.

To further strengthen MGMI and enhance its impact, it is essential that we reactivate all our branches and boost membership numbers. I encourage senior members to take proactive steps in rejuvenating the dormant branches and spearheading membership drives. This concerted effort will not only fortify MGMI's presence across India but also ensure the sustainability and effectiveness of our activities in addressing crucial issues like ecological restoration and the management of surplus mine water.

It is imperative that I acknowledge the successful execution of the 10th Asian Mining Congress and Exhibition organized by our Institute. This landmark event brought together mining professionals, entrepreneurs, researchers, and academics from across the region. The congress provided a vital platform for addressing the challenges faced by the mineral and mining sector, while the exhibition highlighted recent advancements and innovations in the field.

The News Journal continues to receive commendation from its readership for its improved quality and informative content. I extend my heartfelt congratulations to the Honorary Editor and the Editorial Board for their dedication. I encourage them to persist in their efforts to further enhance the journal's content and value for our readers and members. I believe that incorporating constructive feedback from critics can be instrumental in guiding future improvements, ensuring that the journal remains a valuable resource and a beacon of progress in the mining community.

I am confident that everyone here shares my view on the remarkable wealth of knowledge and experience that our MGMI members bring to the table. With such a formidable pool of expertise, we are poised to achieve new milestones under the visionary leadership of Shri Jai Prakash Dwivedi, Chairman-cum-Managing Director, Western Coalfields Limited, Nagpur. His guidance promises to steer our Institute towards unprecedented heights.

As we embark on this new chapter, I extend my wholehearted support to the new team. You can count on my full cooperation, both as an active member and in my role as Past President, to ensure our collective success. Together, let us leverage our strengths and continue to make significant strides in the coal industry and beyond.

Thank you!

Jai Hind.

EDITORIAL

TRANSFORMING MINING : INNOVATIONS, SUSTAINABILITY, AND FUTURE TRENDS

Dr Ajay Kumar Singh

Minerals are vital to modern life, driving economic growth and technological advancement worldwide. They are essential for supplying energy, constructing infrastructure such as roads, bridges, and buildings, and play a key role in manufacturing consumer goods, electronics, and renewable energy systems like solar panels and wind turbines.Minerals such as iron, copper, and lithium drive industrial operations, while rare earth elements are essential for high-tech applications. Globally, the mining sector supports millions of jobs, boosts national economies, and facilitates international trade. Beyond economic contributions, minerals enable Innovations in healthcare, transportation, and communication. Their sustainable management is crucial to balancing resource extraction with environmental protection, ensuring long-term benefits for society while mitigating ecological impacts and promoting global sustainability.

Minerals play a crucial role in driving India's economic progress and contributing to the growth of its GDP. As a key resource for industries such as manufacturing, construction, technology, and energy, minerals like iron ore, coal, bauxite, and limestone are essential for infrastructure development, industrial output, and job creation. The mining and processing of minerals boost employment opportunities and foster regional development. Export of minerals enhance India's trade balance and foreign exchange reserves, supporting economic growth. By supplying raw materials for sectors like automotive, electronics, and steel, minerals contribute significantly to India's industrial competitiveness on a global scale, thereby playing a crucial role in shaping the country's overall economic prosperity.

The coal mining industry in India has been a significant driver of the nation's energy sector for over a century. With vast reserves, India ranks as the second-largest coal producer globally, accounting for approximately 70% of its electricity generation. This sector not only fuels power plants but also supports various industrial processes, including steel, cement, and aluminium production. Over the years, efforts have been made to modernize mining techniques, improve safety standards and increase efficiency through mechanization and advanced technologies. The beneficiation of coal, involving processes like washing and upgrading, has become essential to enhance the quality of coal, reducing environmental impacts and making it more suitable for use in advanced power generation systems. Despite environmental concerns, coal remains a cornerstone for India's energy security, driving growth in regions where mining operations are a major economic contributor.

The Indian metal ore mining and metal industries play a significant role in the country's economy. India is rich in mineral resources, including iron ore, bauxite, manganese, and copper, which are the backbone of its metal industry. The mining sector provides raw materials essential for the production of steel, aluminium, and other metals used in construction, manufacturing, and infrastructure development. The growth of these industries has contributed to job creation, infrastructure development, and industrial advancement. India's metal industry has been adapting to sustainable practices, focusing on environmental regulations and the efficient use of resources. As a global player, India continues to expand its metal production capacity, supporting both domestic and international markets.

Greenhouse gas (GHG) emissions remain a critical concern in the mining industry due to its energy-intensive operations and substantial carbon footprint. However, mining companies are increasingly committing to net-zero emissions and enhancing their Environmental, Social, and Governance (ESG) strategies. By investing in cleaner technologies, improving energy efficiency, and adopting sustainable practices, these companies aim to mitigate their environmental impact. Efforts such as transitioning to renewable energy sources, reducing waste, and promoting responsible resource management are driving the industry toward a more sustainable future.

Industries in India are actively working towards emission abatement and achieving net-zero emission targets by adopting innovative technologies and sustainable practices. Indian researchers are at the forefront of developing Carbon Capture, Utilization, and Storage (CCUS) solutions to reduce greenhouse gas emissions from industrial processes. Initiatives such as integrating renewable energy, improving energy efficiency, and advancing circular economy principles are gaining traction across sectors like manufacturing, power, and cement. Collaborative efforts between industries, government bodies, and academic institutions are driving research on low-carbon technologies and sustainable development. These efforts aim to accelerate the transition to a low-carbon economy and support India's commitment to global climate goals.

The Mining, Geological and Metallurgical Institute of India (MGMI) is dedicated to promoting the development of India's mineral and mining sectors. As a leading platform, MGMI fosters collaboration among entrepreneurs, managers, engineers, and scientists. It provides a space for knowledge sharing, research dissemination, and the development of innovative solutions to address challenges within the mining sector. Through seminars, workshops, and conferences, MGMI bridges the gap between theory and practice, promoting the adoption of sustainable and efficient mining practices. By encouraging publications in its journals, dialogue and innovation, MGMI contributes to the growth and modernization of India's mining industry.

The current edition of Transactions features five insightful technical articles spanning diverse fields. These include : *Recent developments in zinc-lead-silver mining in India, Optimising blasthole drilling performance in surface mines – an innovative approach, Applied mineralogical studies on an iron-rich manganese ore, Decarbonizing the mining industry: strategies and innovations for sustainable practices, and Artificial intelligence in the mining industry.* These articles provide cutting-edge research and practical innovations for professionals in the mining sector. The readers will thoroughly enjoy reading these articles, as they are engaging, informative and interesting.

This edition of the Transactions marks the conclusion of my tenure as Editor of MGMI. As I bring this fulfilling journey to a close, I wish to convey my deepest gratitude to the President of MGMI for his unwavering support and encouragement throughout my tenure. I also extend my heartfelt thanks to the Honorary Secretary for his steadfast assistance and collaboration.I am profoundly grateful to the esteemed Council Members and the Editorial Board for their insightful suggestions and diligent reviews of the articles. My sincere appreciation also goes to the Reviewers and MGMI staff for their timely support and contributions. Lastly, I would like to acknowledge the remarkable efforts of all the distinguished authors whose work has significantly enriched the journal's pages.

Ajay Kumar Singh
Hony. Editor

ADDRESS OF INCOMING PRESIDENT AT THE 118TH ANNUAL GENERAL MEETING OF MGMI ON 21ST SEPTEMBER 2024

Jai Prakash Dwivedi[1]

Distinguished Guests, Respected Members of MGMI, Ladies and Gentlemen,

It's an honor to be here as we gather to focus on the future challenges and the transformative technological advancements that we must embrace. We are standing at the brink of an energy transition globally, one driven by renewable technologies, efficiency improvements, and an acute awareness of our environmental responsibilities.

Around the world, nations are making significant strides in renewable energy, with solar, wind, and other sustainable sources rapidly becoming mainstream. Advances in solar power, such as improved photovoltaic efficiency and solar storage solutions, have drastically lowered costs, making solar energy one of the most economical power sources. In wind energy, advancements in turbine design, offshore wind farms, and energy storage integration are setting benchmarks we can emulate here in India. Embracing and adapting these technologies can position us as a global energy leader and as a proactive participant in sustainable progress.

India's ambitions for clean energy, as outlined in the government's mission programs, provide a solid framework for the industry to support and drive this transition. Initiatives such as the National Solar Mission, which targets 280 GW of solar power by 2030, and the National Wind-Solar Hybrid Policy aim to balance and diversify our energy sources. For us in the mineral industry, this opens new avenues for collaboration and investment in renewable technology, where we can actively contribute to the success of these missions through critical mineral production, essential for manufacturing solar panels, batteries, and wind turbines.

The transition to a low-carbon economy hinges on the availability of critical minerals like lithium, cobalt, and rare earth elements, essential for technologies such as electric vehicles and energy storage. India must position itself to secure these resources sustainably and responsibly, focusing on indigenous exploration, mining, and refining. By doing so, we reduce dependence on imports, create jobs, and establish India as a reliable source for critical minerals globally, all while advancing our renewable energy capabilities.

The adoption of Artificial Intelleence, Internet of Things, and blockchain in the exploration and management of resources will be pivotal. With AI-driven data analytics, we can predict resource availability

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[1] CMD, Western Coalfields Limited

Speech delivered on 21st September 2024 at the 118th Annual General Meeting at Williamson Magor Hall, 3rd Level, Bengal Chamber of Commerce & Industry, Royal Exchange Building, 6 N S Road, Kolkata

The adoption of Artificial Intelleence, Internet of Things, and blockchain in the exploration and management of resources will be pivotal. With AI-driven data analytics, we can predict resource availability more accurately, while IoT can enhance operational efficiency and safety. Block-chain ensures transparency and traceability throughout the supply chain, which is essential in ensuring ethical sourcing, especially for minerals used in green technologies.

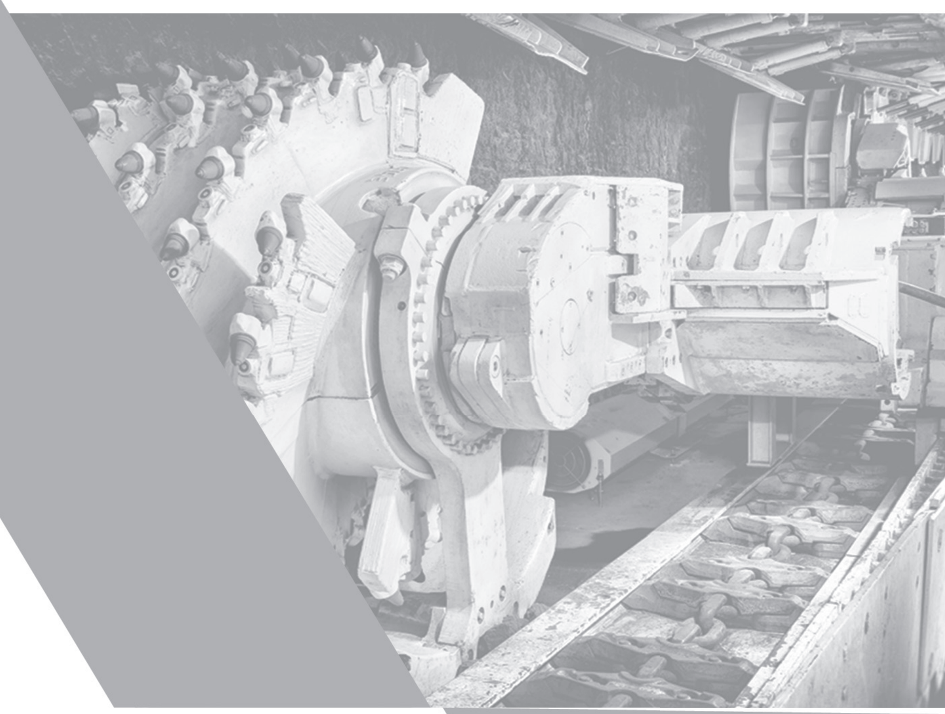
To scale our renewable energy efforts, we must forge partnerships across sectors. The mining and energy industries should collaborate closely with technology developers, policymakers, and academic institutions. These alliances can foster innovation, from cutting-edge research in renewable tech to streamlined solutions for critical mineral extraction.

India has the unique advantage of abundant sunlight, substantial wind potential, and a growing tech-savvy workforce. By aligning our mineral and energy sectors with government priorities, we can set an example for sustainable energy practices and become a leader in renewable energy production and technology. This vision aligns with our government's commitment to international environmental goals, strengthening India's role in the global renewable energy transition.

The future we envision will be challenging, but with each step, each innovation, and each partnership, we move closer to a sustainable and resilient energy future. Let's work together to ensure that India not only meets but exceeds the world's expectations in renewable energy leadership and sustainable mineral practices.

As a torch bearer of Indian Industry interface, it is an onus responsibility of MGMI family to rise to occasion and lead the change process to align the Industry to National priorities serving the humanity, nature and mother Earth. I call upon my MGMI family to commit ourselves towards betterment of life and sustenance. Let each one of us contribute our best to make the World a better place to live in.

Thank you!



TECHNICAL PAPERS

RECENT DEVELOPMENTS IN ZINC-LEAD-SILVER MINING IN INDIA

D. C. Panigrahi[1]

ABSTRACT

The paper outlines India's impressive advancement in zinc, lead, and silver metal production, presently holding the 3rd, 7th, and 11th positions on a global scale for each respective metal. Emphasizing the pivotal role of Hindustan Zinc Limited (HZL) in this advancement, particularly through its underground mining operations, the paper examines the sustainability of metal production based on the country's reserve and resource (R&R) base. It predicts a sustainable period of at least 15 years for current production levels, stressing the need for additional exploratory efforts to expand mineral inventory of the country.

A snap shot of mining activities of the Rampura Agucha (RA) Underground Mine of HZL is provided, showcasing key aspects such as orebody development, ventilation network modelling, level of mechanisation adopted and innovative practices employed to enhance operational performance. The mine, extending from a depth of 500m below the RA Opencast Mine to 970m depth, initially utilized three vertical shafts and a decline from the surface for access. Subsequently, 16 additional openings in the form of intakes and returns (12 intakes and 04 returns) through raise bored boreholes and a ramp punch entry from opencast were introduced to support the ventilation system.

The underground equipment comprises 65T capacity LPDTs, 20/21T LHDs, and longhole drills of varying diameters, facilitating open stopping with paste filling. The total power of diesel equipment operating underground is approximately 40,000 kW. The ventilation system, crucial for maintaining air quality and removing pollutants, is extensive and intricate, supplying 2000 m_3*/s (69.38 million tonnes of air per annum-MTPA) of air with a total installed power of 12,000 kW. Additionally, 3000 Rt (refrigeration tonnes) of air conditioning systems have been installed to support the ventilation system in deeper parts of the mine workings.*

This paper highlights various innovative concepts implemented within the mine. Notably, in FY 2023-24, the RA Underground Mine achieved a significant milestone, producing 4.93 million tonnes of or ealongside a record development of 28.80 km.

Keywords : Zinc, lead, silver, mineral inventory, India's ranking, underground mining, innovative systems.

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INTRODUCTION

An analysis of the usage statistics for zinc metal reveals its position as the fourth most commonly utilized metal at present, after iron, aluminium, and copper. At the same time, lead is valuable to human beings for thousands of years because it is found abundantly, it is easy to extract, and possesses useful properties. Lead is often found together with zinc, silver, and sometimes copper, mostly in the form of the mineral galena (PbS). It is extracted as a co-product along with these metals. Beyond lead and zinc, silver's scarcity, appealing aesthetic qualities, and malleability make it well-suited for applications in jewelry, ornaments, and household silverware. In its natural state, silver can occur in its native form, representing one of the earliest metals mined and utilized by human civilization. The mining and production of silver predominantly occur as a byproduct of lead, zinc, copper, and, to a lesser extent, gold (Au).

In the above backdrop, the paper focuses on development of mining activity for producing metals, viz. zinc, lead and silver, in the country. In India, the zinc ore contains mainly lead and silver. Along with the production of zinc metal from zinc ore,Hindustan Zinc Limited (HZL) recovers lead and silver recovered from the ore. It may be worth mentioning that presently India ranks 3rd in the world in zinc metal production ahead of USA and Australia (https://investingnews.com).

In lead and silver metals, India ranks 7th and 11th respectively in the world. In the last few years, production of these metals in India have increased significantly for placing the country in respectable position. This has been possible due to significant increase in mining activity in this sector.

Further it is to be noted here that total production in this sector comes from underground mining and during last 8-10 years, HZL is mainly focusing on developing some underground mines comparable to best zinc mines of the world. This vision with intensive action on the ground has resulted into development and operationalization of some of the best zinc mines in the world. In recent past, within 3-5 years, some of their zinc mines have occupied as the top zinc metal or zinc ore producing mines of the world. The paper presents the developments in one such mine, viz. RA Mine.

GROWTH OF ZINC, LEAD AND SILVER PRODUCTION

Since 2003, when Hindustan Zinc Limited (HZL) underwent privatization, there has been a notable surge in zinc, lead, and silver production within the country. In 2003, zinc metal production stood at 306,400 metric tons, positioning the country at 9th globally (source: The Global Economy). By 2021, zinc metal production had escalated to 1.3 million tons, marking over a fourfold increase during this period (source: Investing News). Consequently, India ascended to the 3rd position in the world ranking for zinc production (source: Investing News). Figure 1 shows the trajectory of zinc metal production alongside the corresponding changes in the country's global ranking.

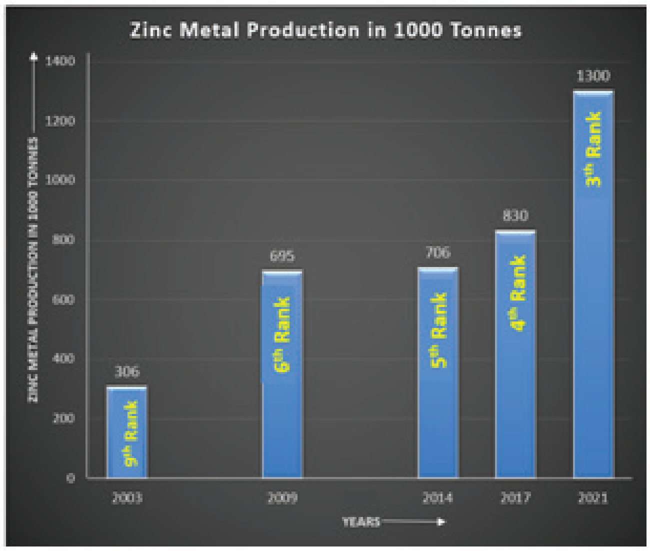


Figure 1: Evolution of Zinc Metal Production over Various Years and India's Global Ranking

Figure 1 illustrates a notable increase in zinc production over the years. Upon observing this steep increase, readers might presume it was driven by an expansion in opencast mining. However, this assumption does not hold true in this context. In the Bhilwara district of Rajasthan, India; the zinc-lead and silver sector primarily relied on a single opencast mine known as RA OC Mine, which reached a depth of 420m by 2013, but was subsequently closed due to various issues. Consequently, further production and growth in this sector stemmed from mechanized underground mining, serving as an instructive example for other industries across the country.

Zinc ore is typically found alongside lead and silver as other minerals. The surge in zinc production also led to a proportional increase in the production of lead and silver, propelling India to the 7th and 11th positions globally in lead and silver production, respectively (sources: investingnews.com & statista.com). This achievement is a matter of national pride, as India has surpassed numerous developed countries in zinc and lead production. Anticipating the closure of RA Mine, a few years prior, Hindustan Zinc Limited (HZL) embarked on a mission to develop and operate some of the world's premier underground zinc mines. This paper focuses the development of one such mine, namely RA Underground or RA Mine.

RESERVE AND RESOURCE STATUS OF ZINC, LEAD AND SILVER METALS

Following the significant increase in production of zinc, lead, and silver metals, it becomes imperative to assess the reserve and mineral resource (R&R) bases of these metals within the country to ascertain the sustainability of future production. This assessment is effectively illustrated in Table 1 provided below :

Table 1 reveals that India possesses sufficient reserve and resource (R&R) potentials to sustain its production for at least 15 years. Apart from Bamnia Kalan, HZL operates mines across all these assets. These mines are actively conducting detailed explorations at deeper levels, thereby continuously augmenting the R&R of these metals within the country. Nonetheless, to escalate production levels of these metals, it is imperative to strengthen additional exploration endeavors aimed at establishing supplementary R&R in untapped regions.

Table 1: Ore Reserve and Mineral Resource (R&R) as on 31st March, 2022

Source: Integrated Annual Report, 2021-22, HZL

Available at: https://www.hzlindia.com/E-Annual-Report/2021-22/journey.html

HZL Assets	**Total Reserve**				**Total M&I**				**Inferred**				**Total R&R (MT)**	**Total Metal (MT)**
	MT	Zn (%)	Pb (%)	Ag (g/T)	MT	Pb (%)	Zn (%)	Ag (g/T)	MT	Zn (%)	Pb (%)	Ag (g/T)		
Rampura Agucha	47.0	11.8	1.3	44	10.3	14.7	2.2	64	17.6	6.0	3.6	97	75.0	9.6
Rajpura Dariba	28.9	4.9	1.6	60	5.3	7.1	2.2	71	33.6	6.3	1.9	96	67.8	5.1
Sindesar Khurd	45.4	3.0	2.0	100	43.8	4.0	2.2	111	15.5	3.4	1.9	96	104.7	5.8
Bamnia Kalan					20.0	3.2	1.1	41	19.5	3.6	2.1	47	39.5	1.9
Zawar	37.9	2.8	1.2	23	36.8	3.4	2.0	28	79.3	3.6	2.1	34	154	8.0
Kayad	1.9	7.6	0.9	18	2.6	8.0	1.1	21	2.4	6.8	0.9	14	6.9	0.6
Total	**161.2**				**118.8**				**168.0**				**447.9**	**31.0**

DEVELOPMENT AND STOPPING METHOD ADOPTED IN RA UG MINE

The mining operation at RA OC mine extended to a depth of 420 meters from the surface. Before 2-3 years of complete closure of RA OC Mine, a 60-meter parting was left and development for underground mining activity was started with trackless mining system. Practically the underground mining started from a depth of 500m and the present depth of working is extending between 600m and 970m.

Within next 5-7 years, the depth of workings will extend to 1.2km. Main vertical entries to the mine are three 7.5m dia shafts and two of these shafts are ventilation shafts up to 450m and third one is used as production shaft equipped with Koepe winding system upto 970m. In addition, the mine has developed a large size Decline of 5.6m x 5.3m for movement of vehicles from the surface. This Decline spanned a length of 2.0 km before dividing into two branches, one to the north and the other to the south, to accommodate the development and extraction of ore along the entirety of the strike direction. The total length of the Decline from the surface to the lowest point on either the north or south side was 6.7 km, with a gradient of 1 in 7. A schematic representation of the mine layout below -80m RL, post the Decline's division into north and south branches, is depicted in Figure 2.

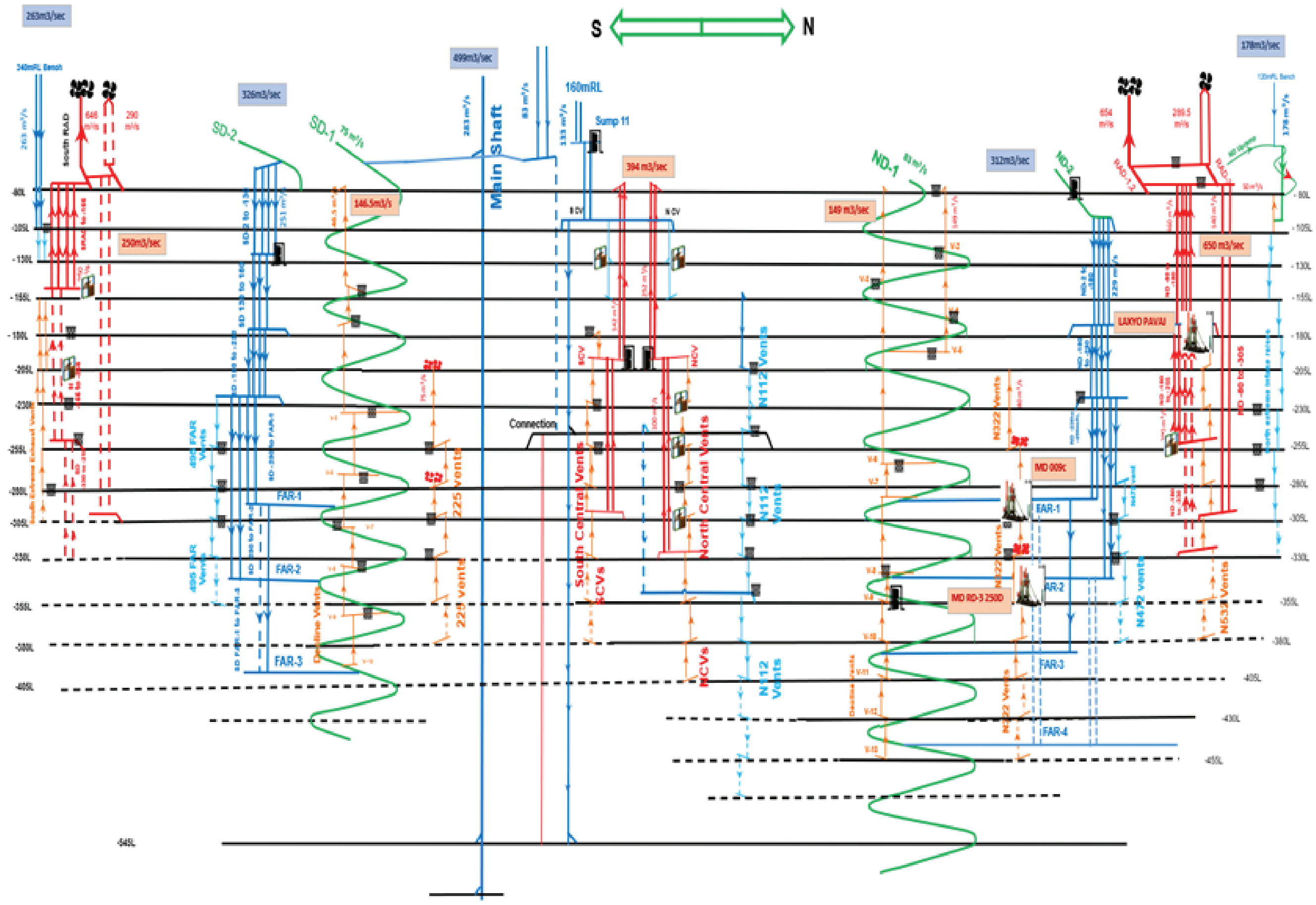


Figure 2: Schematic layout of RA Mines

The mining method employed in the operation involved long hole blasting in open stopes, with paste filling, and a level interval of 25 meters. Drill hole diameters ranged from 89mm to 204mm. Furthermore, the mine utilized large LHDs with a bucket capacity of 20/21 tons, as well as LPDTs with a capacity of 65 tons, multi-boom Jumbos, PCs (Passenger Carriers) etc. LPDTs are hauling up the ores/wastes from a depth of 970m to the surface through Decline(s). The trackless vehicles used in RA Mine are the highest capacity of machines available in the international market and being used by a few leading metal mining companies in the world. At present RA Mine uses nearly 40,000 kW of diesel-power edequipment running within the close underground space and emitting diesel fumes, which is handled by the ventilation system of the mine and the same is presented in the next section of this paper. The details of mine development in 'm' and the ore production in tons are given in Table 2.

Table 2: Yearly Development and Production Progress of RA UG Mine up to FY 2022-23

Financial Year	Development (m)	Production (T)	Remarks
2011-12	529	-	Development in 03 months (Jan-12 to Mar-12)
2012-13	3783	-	
2013-14	7342	-	
2014-15	8464	451844	
2015-16	12221	223521	Production in 6 months (April-15 to May-15 & Dec-15 to March-16)
2016-17	15102	1087380	
2017-18	19417	2078623	
2018-19	24782	3330008	
2019-20	27784	3940100	
2020-21	27598	4272902	
2021-22	29129	4511217	
2022-23	30400	4790021	
2023-24	28090	4930021	

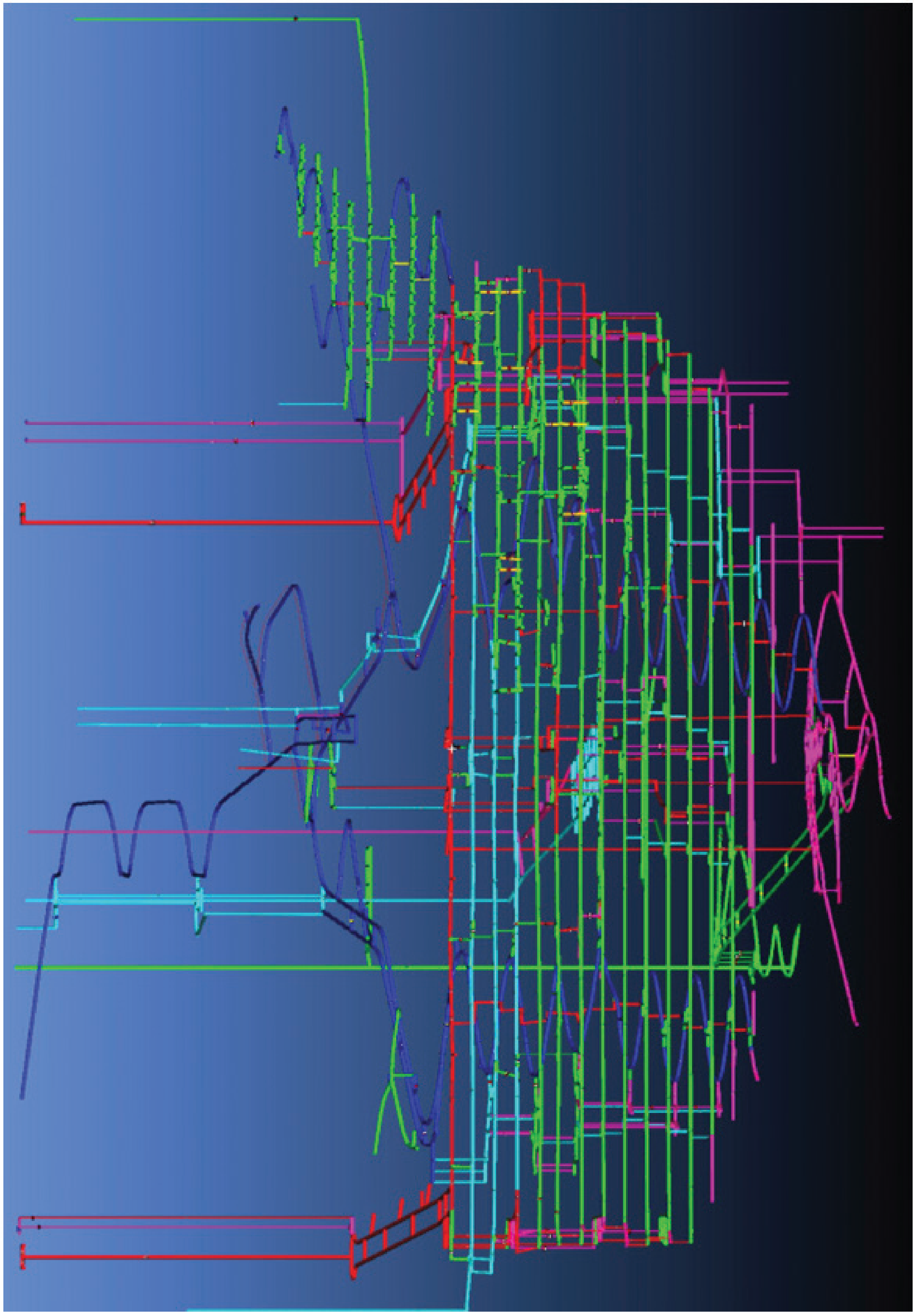
Table 2 illustrates that the mine achieved a remarkable ore production of 4.93 MTPA (million tons per annum) during the fiscal year 2023-24, alongside an impressive development of 28.10 km. With ongoing scaling up operations, the mine is projected to elevate its production to 6.0 MTPA within the next 2-3 years. Renowned for its excellence, this mine stands as a global benchmark among underground operations, having been the world's top zinc metal producing mine in the previous year.

MODELING AND IMPLEMENTATION OF VENTILATION SYSTEM IN RA MINE

It has previously been stated that approximately 40,000 kW of diesel-powered equipment are actively operating within the confined underground environment, emitting substantial amounts of diesel fumes. The ventilation network modeling studies have been conducted by us and devised the ventilation system for a large and intricate mine (Panigrahi, 2022). Since the inception of underground operations in 2012, he has been involved in implementing the designed ventilation network in association with the mine management. Figure 3 illustrates a schematic representation of the ventilation network of the mine. This diagram shows 14 intake air entries and six return openings from the surface. The intake entries consist of a main production shaft of 7.5 meters diameters, a Decline measuring 5.6 meters by 5.3 meters, one Ramp entry from the opencast mine (5.6 meters by 5.3 meters), and 11 raise bored raises, each with a diameter of 3.5 meters. Presently, the mine has six return entries, including two return shafts with a diameter of 7.5 meters each and four raise-bored boreholes, each with a diameter of 3.5 meters. With the depth of the RA Mine already exceeding 850 meters and encountering issues with strata heat, the ventilation network modeling encompassed various crucial phenomena as mentioned below to comprehensively design the mine's overall ventilation and air-conditioning system :

1) Airflow in the network
2) Transient heat flow from strata, machines etc.
3) Diesel fume propagation and its concentration
4) Installation of air conditioning system and its impact on workplace environment.

It may be worth to be noted here that total rating of main fans installed on the surface is in the order of 12000 kW handling total air quantity of 2000 m_3/s exhausted by the system and in terms of mass flow rate, it is 69.38 MTPA (million tons of air per annum). Since production of the mine will be raised from this year's target of 4.93MTPA to 6.0 MTPA within 2-3 years, ventilation system of the mine is already upgraded to 2000 m_3/s (69.38 MTPA of air) in advance.



In addition, the air conditioning systems of 3000 Rt (refrigeration tons) has been installed for cooling intake air to lower levels.

This is the highest capacity ventilation system amongst all underground coal and metal mining operations in the country.

INNOVATIVE PRACTICES ADOPTED IN RA MINE

It is not possible to achieve the sustainable high development rate, high production and productivity without adopting innovative practices. Always Innovation Group of the mine is focused to bring innovative practices to ride up the high-performance ladder. The different innovative thoughts/practices adopted in RA Mine are as follows:

i) **HighSpeed Shaft Sinking :** The sinking of three lined vertical shafts, viz. one production shaft of 7.5m dia up to a depth of 970m, two ventilation shafts each of 7.5m dia up to a depth of 450m on north and south sides, were started simultaneously. The high-speed shaft sinking and equipping have been carried out by M/s Shaft Sinker, South Africa and they are considered world leader in shaft sinking and equipping. The sinking and lining of ventilation shafts were completed in 2 years and handed over to HZL management. The main production shaft with lining, installation of Koepe winding system and all other armoring of the shaft were completed within 4 years. They used multi-boom jumbo drills for drilling holes at the shaft bottom, adopted mechanized loading and a number of innovative methods and achieved an average progress of approximately 50m per month in shaft sinking with lining. This high-speed shaft sinking was adopted for the first time in the country.

ii) **Raise Boring :** This has also been adopted for the first time in the country. In this method raise bored boreholes are drilled with 3.5m dia up to 800m depth from surface at some critical locations as decided by ventilation network modelling studies carried out by PMRC Private Limited, Dhanbad subject to availability of surface rights. This technology is not available in India and M/s Master Drills, Australia is hired to execute this job, which has provided a lot of benefits to the ventilation system of the mine.

iii) **Loading and transport machines :** The mine uses the largest size of LHDs with 20/21T bucket capacity, 65T LPDT, multi-boom jumbos, PCs (Passenger Carriers) etc., the largest sizes of all these machines available in international market and are used only in a few mines of the world.

iv) **Paste filling in stopes:** For the first time in India, this mine adopted cement and mill tailing paste filling techniques for filling of voids in stopes, which has better water draining out and compaction properties matching with production and stope filling cycle.

v) **Digitalization in underground :** The wi-fi system is operating in the total Decline length of 6.7 km and it is extended to certain levels of the mine as per the requirement. Some of the LHDs and long-hole drills are remotely controlled from surface. Especially in shift end, LHDs in some levels clear faces to allow the drill jumbos to start drilling at the earliest in the next shift.

vi) **Largest capacity ventilation system :** North and south ventilation shafts house 8000kW of main ventilation fans, i.e. 4000kW of main fan in each up-cast shaft. Four boreholes, i.e. two boreholes on each side of 3.5m dia connected by a common duct in their mouth and a fan system of nearly 2000kW has been installed. Therefore, in both north and south sides 4000kW of main fans (2000kW on each side) have been installed. This makes total installed power of 12000 kW for main fan systems, which are in operation. All these fan systems are operated through VFDs (variable frequency drives), where speed of the fans is changed in flick of a second for increasing or decreasing the air quantity handled by main fans.

The introduction of above innovative thoughts are giant steps taken by HZL in the history of development of underground mining activity in the country. There are many other nuts and bolts type innovations and these are not mentioned here.

CONCLUSIONS

In light of the comprehensive analysis presented in this paper, several key conclusions emerge:

1) The remarkable growth in zinc metal production within India from 2003 to 2023, soaring by fourfold from 306,400 TPA to 1.59 MTPA in 2023, has propelled the country's ranking to the third position globally. This surge has not only surpassed numerous developed countries but has also catalysed the growth of lead and silver production, elevating India to the 7th and 11th positions respectively on the global stage. Such achievements evoke a sense of pride among Indians and particularly within the mining community.
2) With India boasting a robust Reserve and Resource (R&R) base of 447.9 MT for zinc, lead, and silver ores, there exists a solid foundation for sustaining production for the next 15 years. However, it is imperative to intensify exploration efforts to augment these reserves, ensuring the longevity of production for these crucial metals.
3) The remarkable performance of RA Mine, achieving record-breaking milestones such as 28.80 km development below 600m depth and achieving a production peak of 4.93 MTPA in FY 2023-24, instils confidence in the capabilities of underground mining. With aspirations to reach 6 MTPA within the next 2-3 years, this underscores the importance of embracing cutting-edge technologies and innovative approaches to ensure continued success in the mining sector.
4) The ventilation system implemented in RA Mine stands as a testament to engineering prowess and innovation, designed to effectively manage the challenges posed by diesel fumes, strata heat, machine-generated heat, and moisture accumulation. With an exhaust capacity of 2000 m3/s and a total installed power of 12,000 kW, supplemented by 3000 Rt of refrigeration systems, the ventilation system serves as the lifeline of the operation. A comparison with other major coal mining operations in India highlights the sheer scale and magnitude of RA Mine's ventilation system, underscoring the author's innovative contributions in its design.
5) The ethos of "Innovate or fall behind," advocated by HZL's Senior Management, has spurred the implementation of various ground-breaking initiatives within the Indian mining landscape. From high-speed shaft sinking to digitalization in underground operations, HZL continues to pioneer innovative solutions, setting new benchmarks for the industry. As the company sets its sights on further innovative endeavours, the legacy of ingenuity and forward-thinking remains ingrained in its operations, shaping the future trajectory of the mining sector in India.

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OPTIMISING BLASTHOLE DRILLING PERFORMANCE IN SURFACE MINES – AN INNOVATIVE APPROACH

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ABSTRACT

Blasthole drilling in surface mines is a cost-intensive process and optimizing penetration rate assumes significance for overall cost reduction per meter of drilling. The current study aims to propose a suitable drill operating regime based on a new index, namely, drill vibration index(DVI), considering operating parameters and the size of drilling cuttings obtained during drilling process. The study site was selected based on the productivity and utilization of drill machines. The in-situ rock hardness was measured as per ISRM suggested method. The Rate of Penetration (ROP) for each drilled hole was calculated and the drill cuttings obtained for each hole were analyzed using sieve analysis. The mean particle size (d) and characteristic particle size distribution curves for the drilled holes were plotted using sieve analysis and Rosin-Rammler (RR) diagram. Based on the mean particle size, ROP and machine vibration, a Drill Vibration Index (DVI) is introduced as an indicator of vibration severity of the drill machine, and its relationship was studied with ROP and average mean particle size. The DVI obtained was in range of 0.50-1 with average ROP in range of 0.82 to 0.95 m/min. The drill machine with DVI=1 or above is found to have poor performance with higher vibration and production of more fine drill cuttings. The study can be fine-tuned to improve its predictability with more varied cases.

Keywords : Drill machine vibration, rate of penetration (ROP), drill cuttings, mean particle size.

INTRODUCTION

The increasing demand for coal production to meet the energy requirements has led to intense mining activity in India, more so from surface mines, producing 686 MT (94% of total coal production in the year 2018-19). The surface mining operations mainly involve drilling, blasting, loading, hauling and dumping of rock/coal. Drilling being the initial stage of the mining operation, any inefficiency in this has a cascading effect on other mining activities. The machine deployed for drilling is called a blast-hole drill machine (Karpuz, 2018). The necessity to increase the production rate in the field of mining engineering has led the drill machine manufacturers to develop more advanced machinery having a high operating range. The main objective behind all advancements that took place was to improve the drilling performance with lower damage to the drilling components and to ensure safety during the drilling operation. However, during drilling operation, excess machine vibrations are often encountered due to varied rock mass and sub-optimum opera-

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tion. This has resulted in failure of drill components, instability, bit wear, inadequate particle size generation, and low penetration rate. Therefore, it is essential to optimize the drilling process for its improved performance.

LITERATURE REVIEW

Vibration is a significant parameter in rock drilling. Excessive vibration led to drill string component failure as well as can be hazardous to operator health and comfort. Vibration generation during rock-bit interaction is caused due to improper adjustment of drilling operating parameters (Omojuwa et al., 2011, Aldred *et al., 1999,* Pabon *et al., 2010).* Vibration can cause severe damage to drill tools such as drill bit, leading to reduced drilling efficiency by absorbing some of the energy transmitted to the drill bit by the rotary head. Studies have shown that 2-10% of the drilling cost escalates due to machine vibration generation (Branscombe, 2010, Jardine et al., 1994, Ghasemloonia *et al., 2015).* Vibration in drilling is a complex process occurring in axial, lateral, and torsional modes. Among these modes, the axial and lateral mode of vibration causes 75% of drill string failures (Sotomayor *et al., 1997,* Li *et al., 2010,* Kriesels *et al., 1999)*. Thus, drilling companies are continuously engaged in developing technologies and methods to suppress unwanted vibration while drilling. Researchers' interest in the investigation of drilling vibration initiated since the early sixties. Since then, there have been increasing interest in solving drilling vibration using experimental, analytical, and numerical techniques. Qiu *et al., (2017)* used finite element method to investigate the drill string vibration during rock-bit interaction under combined deterministic and random excitation. The mean and standard deviation of bit displacement and rotational speed were obtained and analyzed to develop the drill string vibration model. Hovda, (2018c), Hovda, (2018b), Hovda, (2018a) developed dynamic-semi-analytical-lumped-multi-element models for axial and torsional vibration. Since then, several models were proposed with modification and were also used in many other investigations (Nogueira and Ritto, 2018, Real *et al., 2019*, Zhu *et al., 2019).* Aarsnes and van de Wouw, (2019) considered axial-torsional drill string model to investigate the axial and torsional drill string vibration caused due to regenerative effect during rock-bit interaction. de Moraes and Savi, (2019) also considered the four-degree of freedom non-smooth model for drill string vibration analysis. Lobo et al., (2020a) analyzed the axial-torsional coupled drill string vibration during the rock-bit interaction. The study proposed the novel stochastic process to model rock strength variation during rock-bit interaction for the drill string vibration analysis. Lobo *et al., (2020b)* proposed the lumped parameter model to study the dynamics of laboratory rig designed to reproduce axial-torsional vibration of drill-string in drill operation. Li *et al., (2020)* investigated the lateral vibration based on numerical modelling and analyzed the effect of drilling and borehole parameters on lateral vibration. However, the drawback of previous research related to drill string models was absence of a correlation of drill vibration with ROP, which has been carried out in the current investigation

METHODOLOGY

Study site

Based on the production capacity and deployment of Heavy Equipment Mining Machineries (HEMMs), the investigations were performed in two open cast mining projects, i.e., Dudhichua opencast mine and Nigahi opencast mine of Singrauli coalfield (NCL) located on the northernmost coalfield of Son-Mahanadi basin, Sidhi district of Madhya Pradesh. It lies between the latitudes 23° 47' – 24° 15' N and longitudes 81° 48' – 82° 52' E, covering an area of over 2,200 km^2.

In-situ rock hardness measurement

Rock surfaces at the experimental location were initially cleaned to avoid any distortion in reading due to loose materials. Schmidt hammer rebound values were determined by applying the ISRM suggested methods. This provides in-situ rock competence for the top portion where the drilling operation starts and stabilizes. An area with 1m X 1m was marked at the sites and divided into 16 square blocks of 25cm X 25cm. The Schmidt hammer was held downwards, as shown in Fig.1 in a vertical position, and 20 sets of values were recorded from a single impact. These values were then averaged to get the final rebound value, as shown in Table 1. (Kumar *et al., 2020)*

Drill cuttings measurement

During the present study the net drilling time and the drill depth were recorded after each drilling. The drill depth was measured using the steel tape, and the time taken for drilling was measured using a stopwatch. The rate of penetration was calculated using equation (1).

$$ROP = \frac{D}{T} \text{ (m/min)} \qquad (1)$$

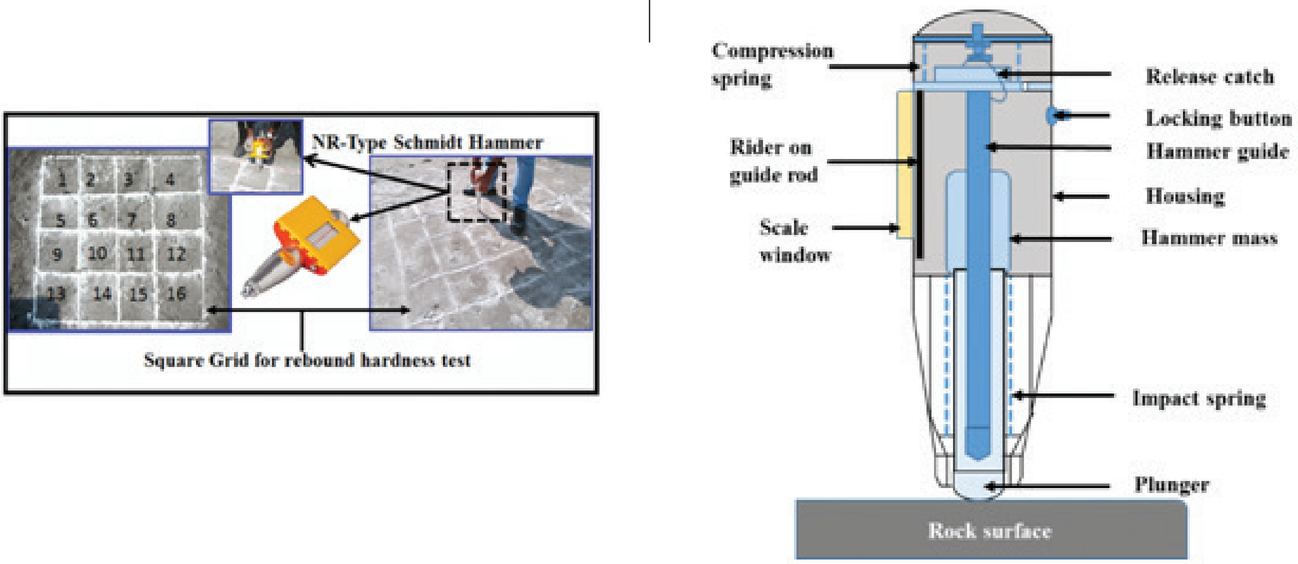


Fig.1 Schmidt hammer rebound hardness test

Table 1 : Configuration of rotary drill rig and the rock hardness

Mine Location	Drill Machine Model	Rock hardness (N/mm^2)	Bit Diameter (m)	Rotation pressure (MPa)	Pull-Down pressure (MPa)	Air pressure (MPa)	Rotational speed (rpm)
Site 1	DM-H Ingersoll Rand	16.38-24.64	0.311	0-39.23	0-27.5	0-2.94	0-200
Site 2	DM-H Atlas Copco	16.33-21.28	0.311	0-39.23	0-27.5	0-2.94	0-200

where, D = drilled hole depth (m); T= total drilling time (min).

On completion of blast-hole drilling, the drill cuttings deposited near the blast-hole were collected for laboratory analysis as shown in Fig.2. The drill cuttings reveal how efficiently the power transmitted by the motor to the drill bit is utilized in cutting. The size of drill cuttings is related to the penetration rate and is of great importance in the estimation of penetration rate and also the machine vibration.

Drill machine vibration measurement

The machine vibration was measured by Piezoelectric IEPE accelerometers at different rotational speeds (80, 85, and 90 rpm). Theseaccelerometers were mounted with the help of a mounting clip.

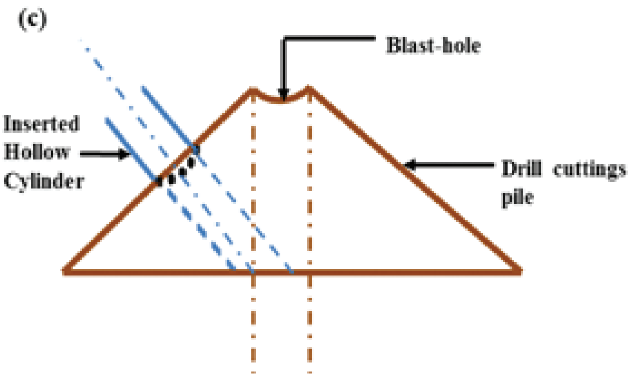


Fig.2 (a) Method of drill cuttings collection

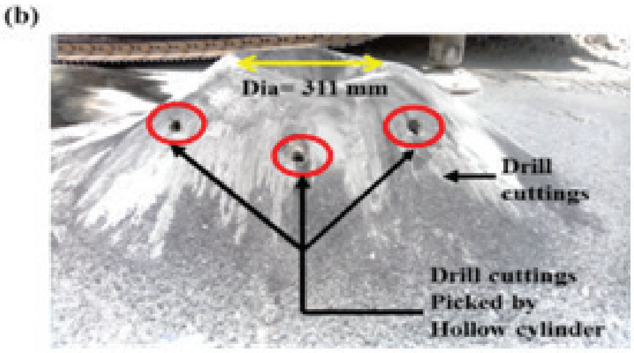
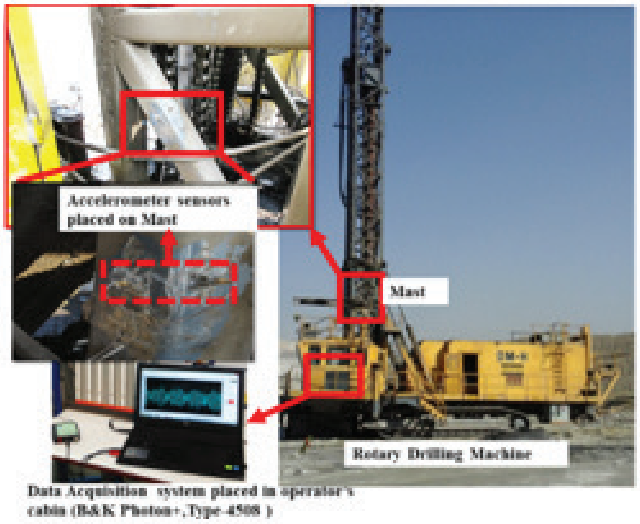


Fig.2 (b) Method of drill cuttings collection

It is attached to the surface with an adhesive on the mast of the drill machine to measure vibration generation during the drilling process along lateral (side-to-side, X-axis) and axial (longitudinal motion along drill string, Y-axis) directions.These sensors record acceleration attained through variation of operating parameters, which are then sent to the primary system through the data acquisition system, as depicted in Fig. 3.



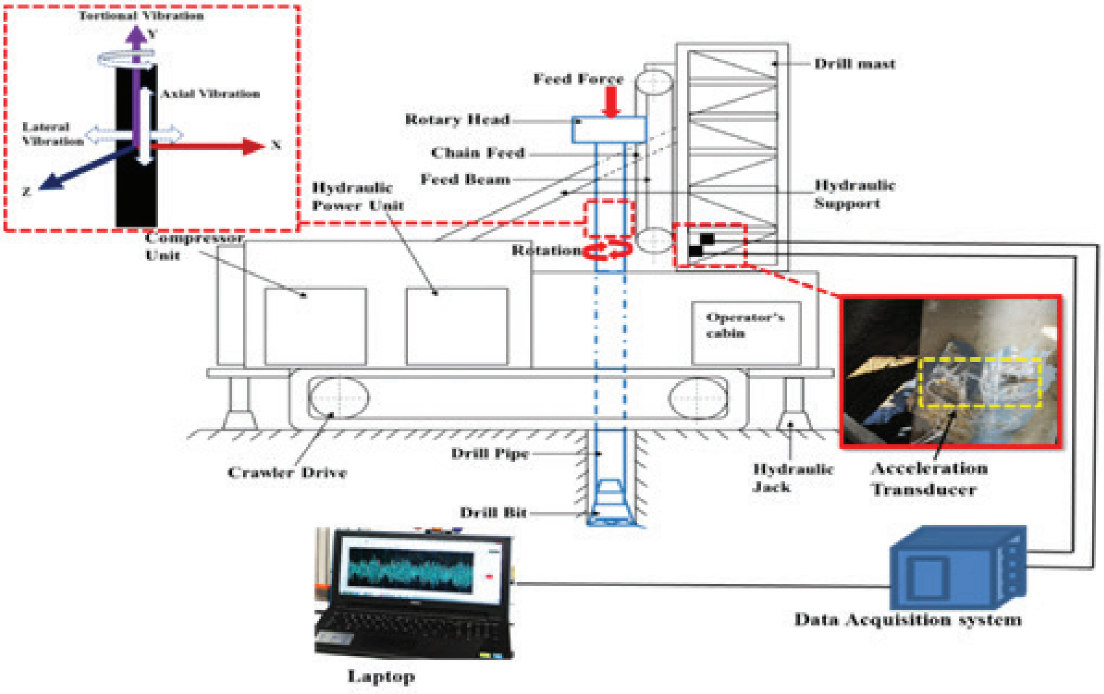


Fig 3. Schematic representation of vibration measurement on drill machine

RESULT AND DISCUSSION

Drill machine vibration data analysis

The vibration data were collected using accelerometers. Two sensors were used and placed at the mast, one oriented to the axial direction and the other to the lateral direction. The signals were recorded by a data acquisition system. The raw vibration magnitude recorded by the vibration analyzer was studied using RMS (root mean square) method, which is represented by equation (2). (Kumar *et al., 2019).*

$$V_{RMS} = \sqrt{\frac{1}{T}\int_{t_1}^{t_2} V_i(t)^2\,dt}\ \text{(m/s}^2\text{)} \qquad (2)$$

where, V_{RMS} = Vibration RMS value, T = time period and V_i = Instantaneous acceleration value. The RMS method is an effective way of analyzing the vibration signal. Fig 4 shows the raw vibration signals and RMS signals collected during the vibration study at three different rpm, i.e., 80, 85, and 90 rpm.

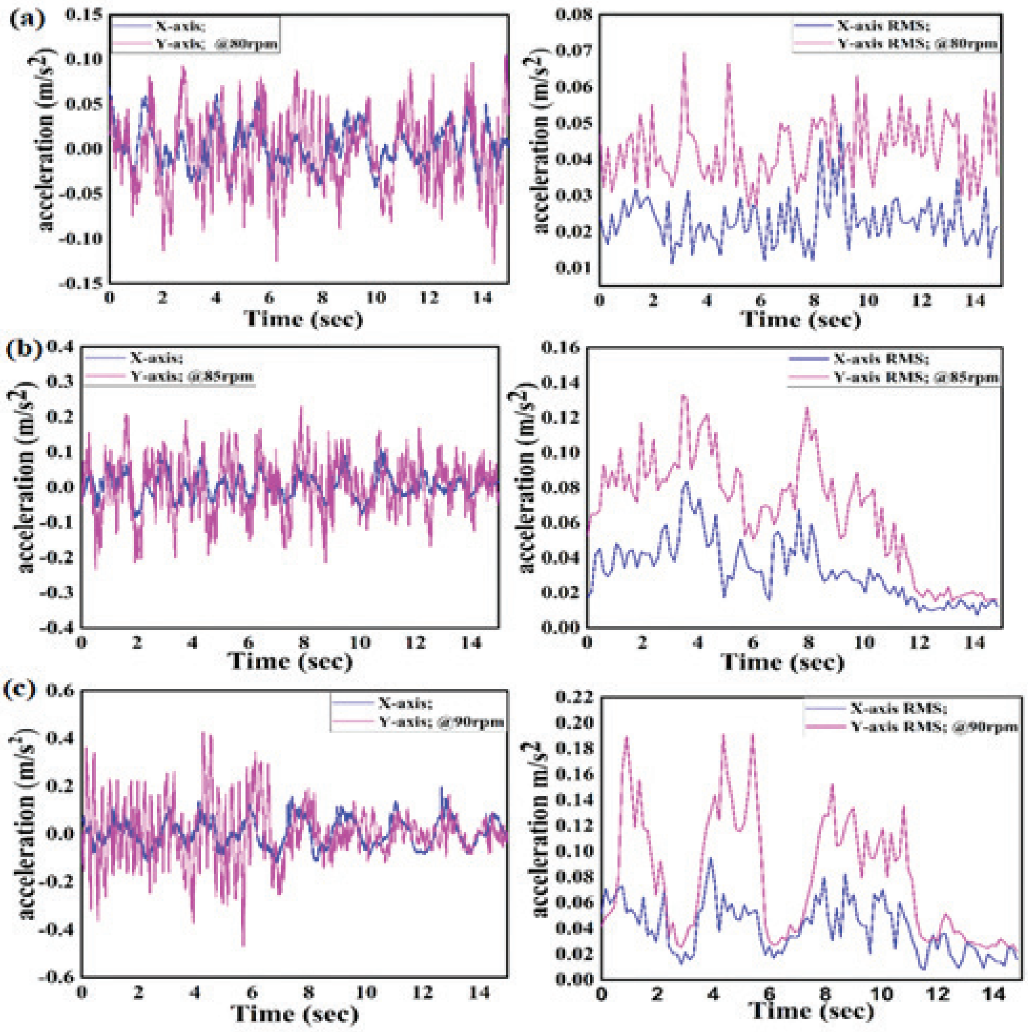


Fig 4. Blast-hole drill time-domain data for vibration (a) at 80 rpm (b) at 85 rpm and (c) at 90 rpm

The signal was recorded during the entire drilling process at each hole which was then normalized for the period of 15 sec. The results obtained show the maximum acceleration of 0.07 m/sec^2, 0.13 m/sec^2, 0.19 m/sec^2 along axial direction (i.e Y-axis) and 0.05 m/sec^2, 0.08 m/sec^2, 0.09 m/sec^2 along lateral direction (X-axis) at 80,85 and 90 rpm. Acceleration obtained shows that the vibration along the axial direction is more in comparison to the lateral direction. Vibration increases with the variation of rock properties, changes in lithology, with boulders, and due to the unsuitable drilling parameters for the rock type. An increase in the intensity of vibration varies depending on the rpm and the resistance offered by the rock while cutting. As the drilling progresses, there is an increase in vibration due to reduced bit penetration, bit stick-slip condition, and inefficient borehole cleaning due to inadequate air pressure. Moreover, the hard surface occurring at the bottom results in instability of the drill string, which leads to vibration.

To analyze vibration signals, Fast Fourier Transform (FFT) was utilized as an effective way of computing the signal so obtained at different rpm i.e., 80, 85 and 90 rpm. The processes decompose the discrete signal into different components of frequencies. Fig 5 shows the FFT graph obtained for three blast-hole with a peak amplitude of 0.022 m/s^2 at 10 Hz along Y-axis (axial direction) at 80 rpm, 0.06 m/s^2 at 10 Hz along Y-axis at 85 rpm and 0.081 m/s^2 at 10 Hz along Y-axis at 90 rpm. Conducting such an experiment at the mine site could be time-consuming and extremely challenging. This experiment was carried out at the maximum operating limit of 90 rpm as set by the operator according to the OEM, standard operating practice.

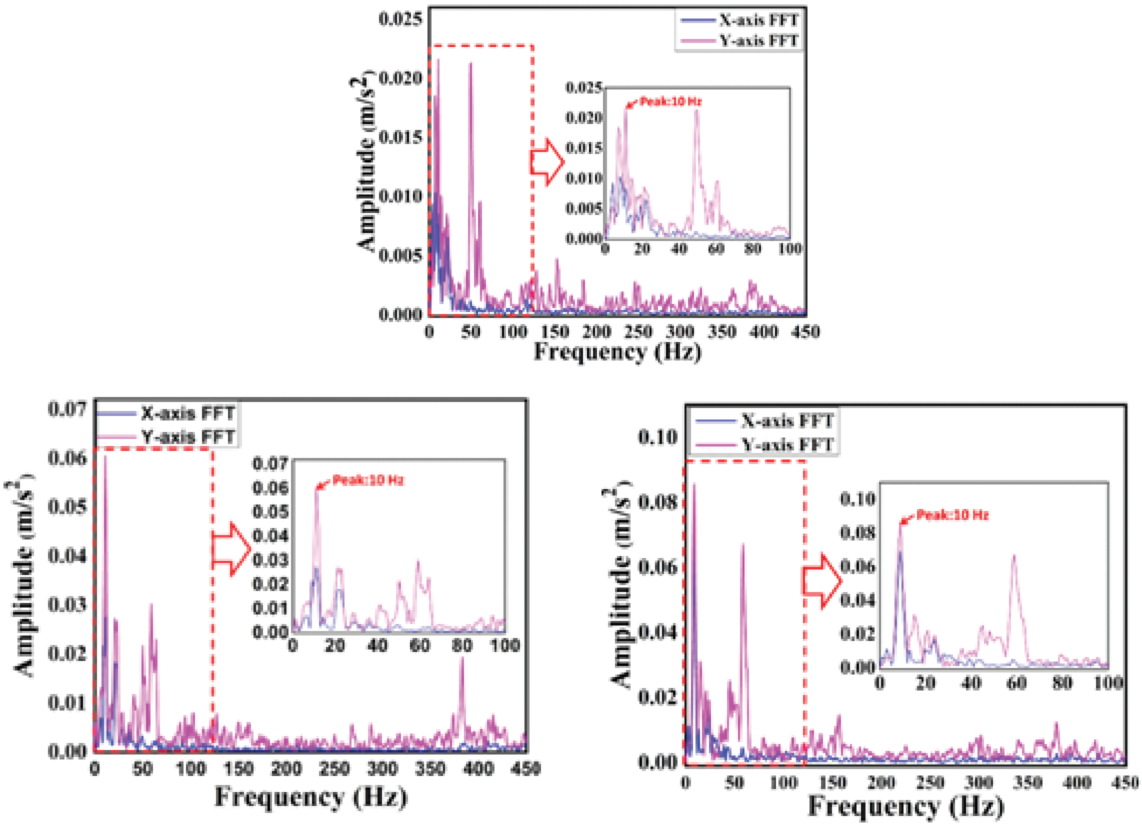


Fig. 5. FFT plot for vibration at rotational speed: (a) 80, (b) 85, and (c) 90 rpm

Mean drill particle size (d)

The mean drill particle size or 'd' is defined as the average size of drill cuttings being generated in blast-hole drilling and is used as an indicator of drilling performance, i.e, rate of penetration (ROP). It is determined by using Rosin Rammler(RR) or Rossin-Rammler Sperling-Bennet (RRSB) graph, proposed from sieving analysis on powdered coal in 1933 (Rosin, 1933). Mean particle size can be obtained from the two parametric functions, as given in equation (3).

$$R(d)=100e-(\frac{d}{d_m})^n \qquad (3)$$

where, R(d) = cumulative weight percentage retained

d = mesh or particle size (mm)

dm= mean particle size (mm) and

n= particle size distribution parameter.

In this investigation, RR diagram (as shown in Fig 6 (a) has been obtained using the Matlabtool with a GUI designed and calculation of distribution parameters, viz. 'd' and 'n' was based on experimental data.

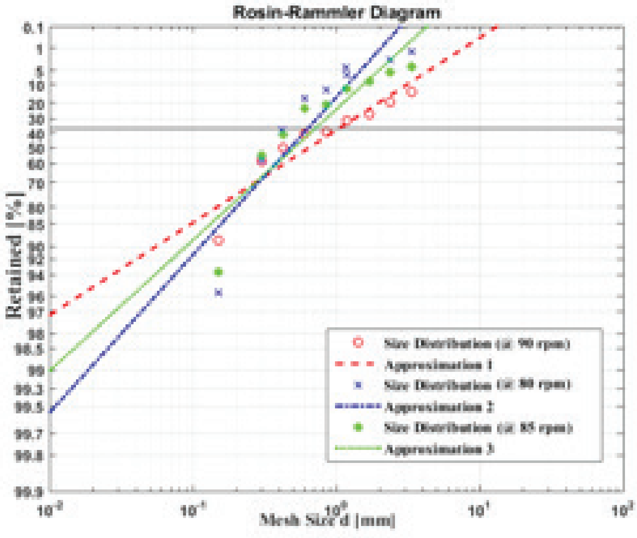


Fig.6. (a) Rossin-Rammler plot

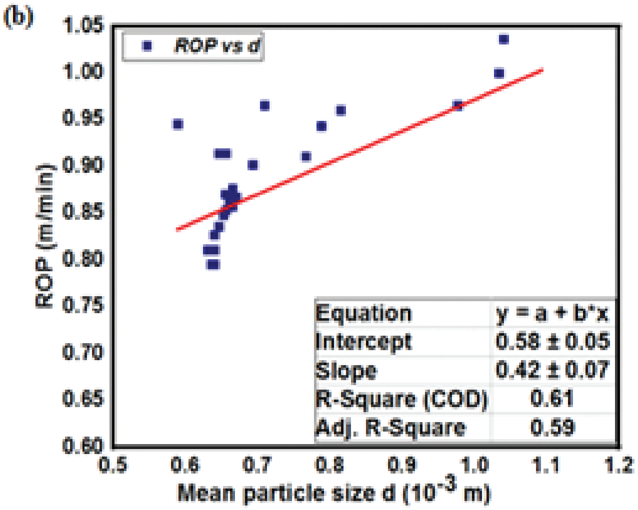


Fig.6.(b) ROP versus mean particle size "d" plot

The mean particle sizes obtained for different rotational speeds, i.e., 80, 85, and 90 rpm were 0.63 mm, 0.71 mm, and 1.04 mm, respectively. Similarly, the particle size was calculated for the rest of the samples obtained after each blast-hole drilling. The Rossin-Rammler plot obtained using the Matlab for the three samples at varying rotational speed of 80, 85 and 90 rpm. During the investigation, the ROP was found to increase with an increase in d. With a correlation of R^2= 0.61, the correlation plot for the ROP and mean particle size (d) is shown in Fig.6(b).

Correlation of Vibration with Operating Parameters

Fig. 7 depicts the vibration measurement data along the axial and the lateral direction with the variation of operating parameters gathered during the drilling process. From the plot, a decreasing trend is observed in both axial vibration and lateral vibration with increasing pull-down force, torque, and rotational speed, while correlation data are unevenly distributed. This suggests that machine vibration reduces as the ROP increases. This is due to proper engagement of the drill bit in cutting rock thus reducing energy loss.

The resultant vibration magnitude, while drilling, is obtained to identify a more accurate trend and also to obtain the optimal condition for the rock drilling. The resultant vibration can be expressed as in equation (4) :

$$V_r=\sqrt{\left[(V_a)^2+(V_l)^2\right]} \qquad (4)$$

where, V_r = resultant vibration (m/s^2), Va = axial vibration (m/s^2) and Vl = lateral vibration (m/s^2). The resultant vibration magnitude is obtained using equation (5), and it is seen that lateral vibration shows a linear relationship with axial vibration having a correlation coefficient R^2= 0.51, as shown in Fig. 8.

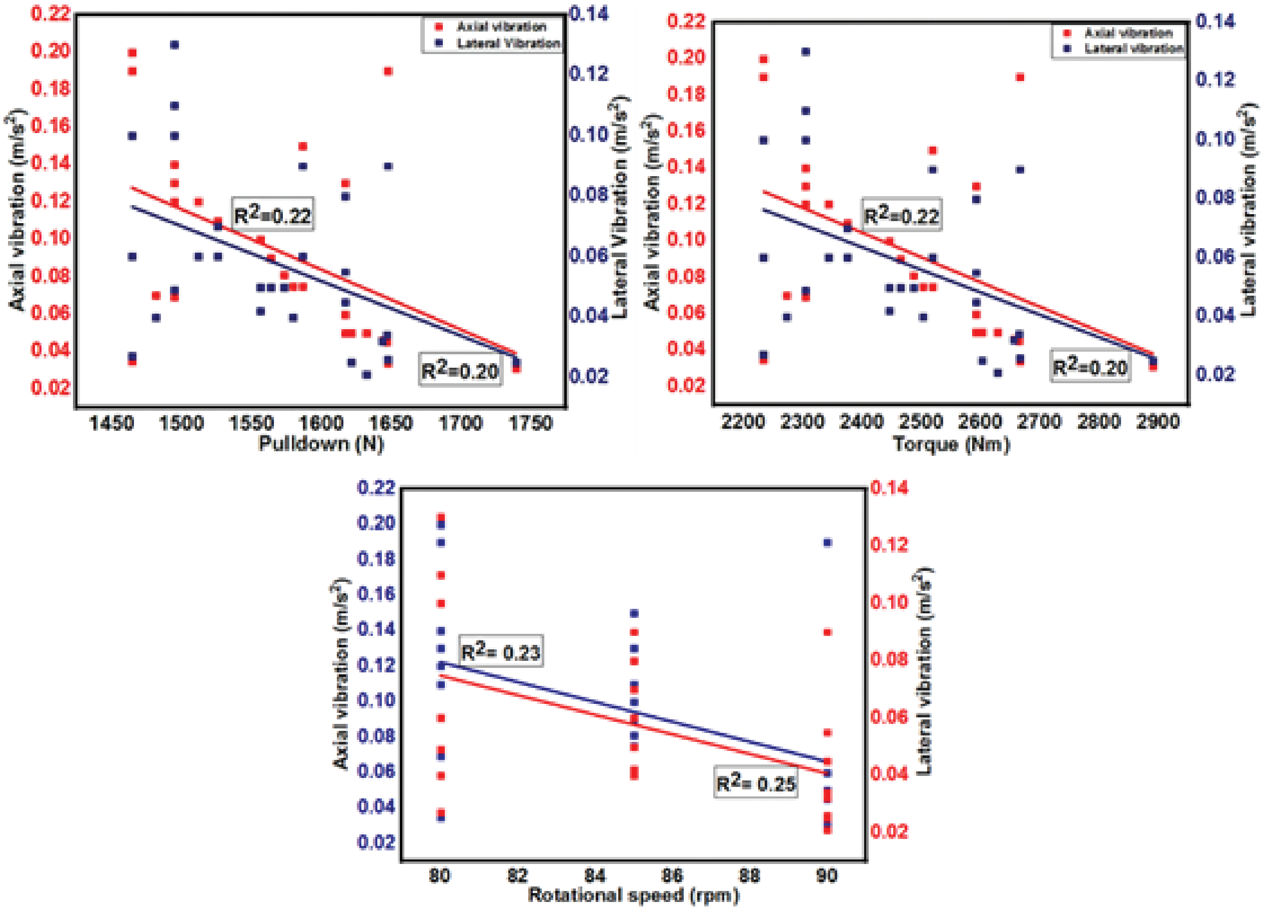


Fig. 7 Correlation plot of vibration with pull-down force, torque and rotational speed

Excess vibration generated due to rock-bit interaction also leads to a poor penetration rate. Choosing a proper operating range thus is crucial. A machine vibration of 0.1g is considered unpleasant, and is intolerable at 0.5g. However, the drill experience vibration up to 0.3g (Christoforou and Yigit, 2001, Wictor, 1991). Hence during the rotary drilling process, it is essential to optimize the operating parameters to reduce vibration generation and to improve drilling rate with less damage to a drill bit. Fig. 9 shows the variation of ROP and resultant acceleration with variation in operating parameters. It is seen that the ROP is directly proportional to pull-down force and torque, showing a good correlation of R^2=0.75 at varying rotational speeds. The resultant vibration decreases with an increase in the ROP, having a correlation of R^2 = 0.25. The optimal condition can be ensured with pull-down force in the range of 1560-1600 N and torque in the range of 2470-2500 Nm with ROP at 0.89 m/min. The resultant vibration and RPM observed for these conditions is 0.10 m/s^2 and 85 rpm respectively.

Development of Drill Vibration Index

A new term Drill Vibration Index (DVI) is introduced in this research to define the vibration severity more precisely and to explain its relationship with the rate of penetration (ROP) to enhance the drill performance prediction. The Drill Vibration Index can be obtained as:

$$DVI = \frac{V.M}{V.M_{avg}} \qquad (5)$$

where, V.M= Vibration Magnitude (m/s^2)

V.Mavg.= Average Vibration Magnitude (m/s^2)

Table 2 shows the average drill performance at various operating conditions with directional vibration and resultant vibration. The new term Drill Vibration Index (DVI) shows a good correlation with ROP as depicted in Fig. 10.

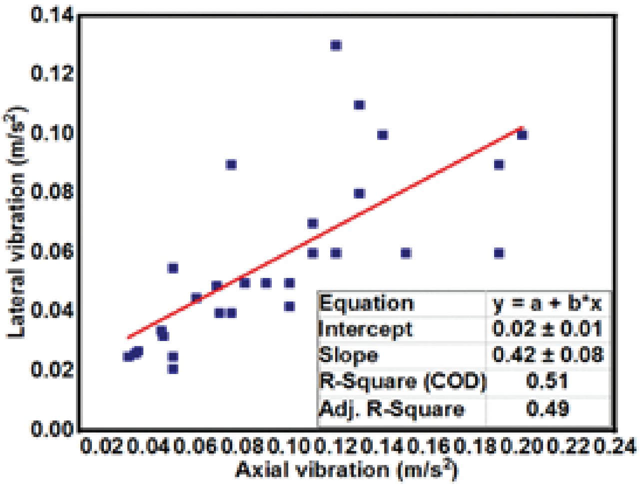


Fig. 8 : Resultant vibration magnitude

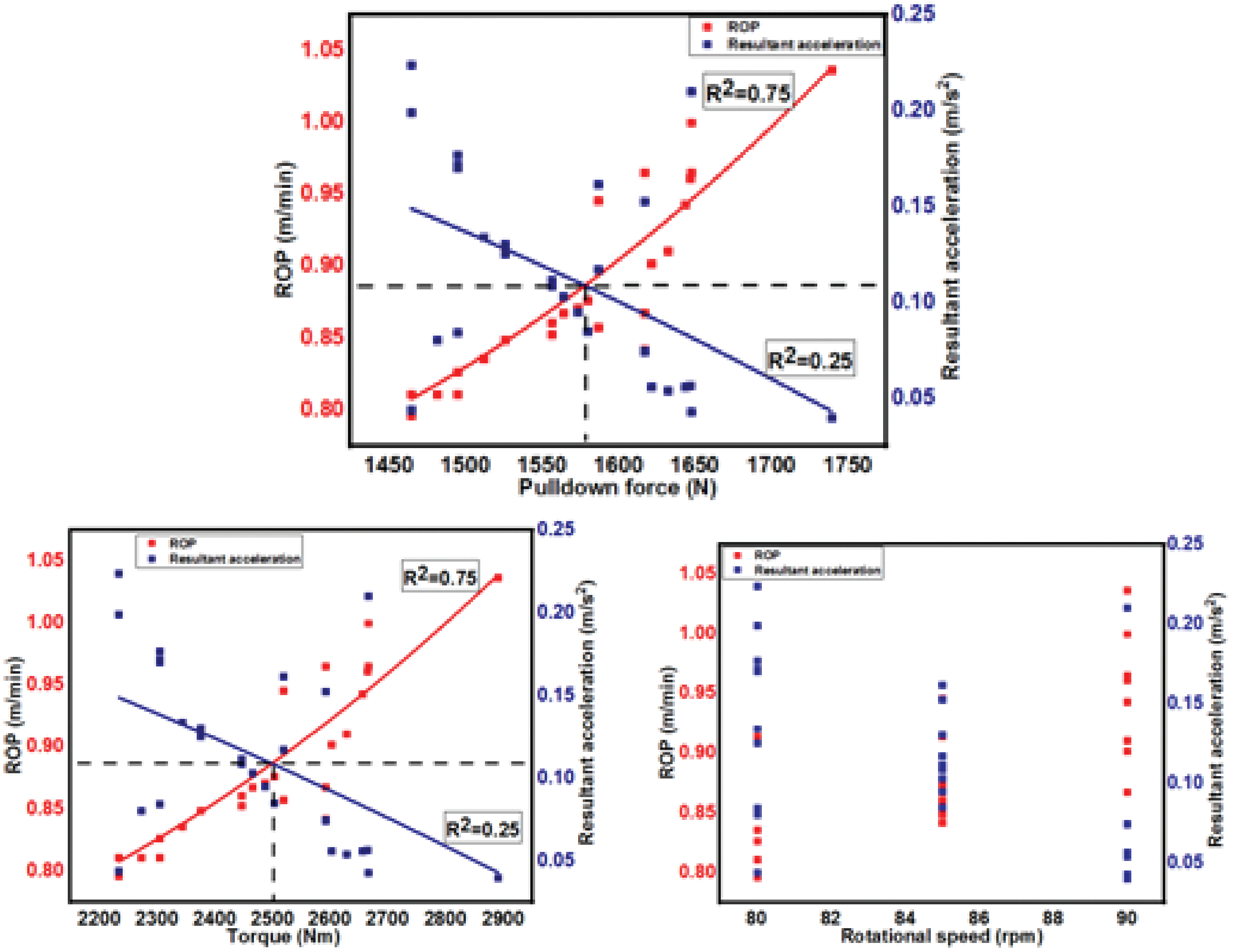


Fig. 9 ROP and resultant acceleration versus pull-down force, torque and rotational speed plot

Table 2: Blast-hole drill (BHD) performance at varying operating parameters

Drill ID	Rotational speed	Pull-down force $_{avg}$	Torque $_{avg}$	ROP$_{avg}$	d$_{avg}$	Axial Vib$_{avg}$	Lateral Vib$_{avg}$	Resultant Vib$_{avg}$	DVI
	Rpm	N	Nm	m/min	mm	m/s^2	m/s^2	m/s^2	
BHD-1	80	1489.39	2290.67	0.82	0.65	0.15	0.09	0.17	1.55
BHD-2	85	1567.14	2472.46	0.87	0.65	0.09	0.06	0.10	0.95
BHD-3	90	1645.99	2661.57	0.95	0.92	0.04	0.03	0.05	0.50

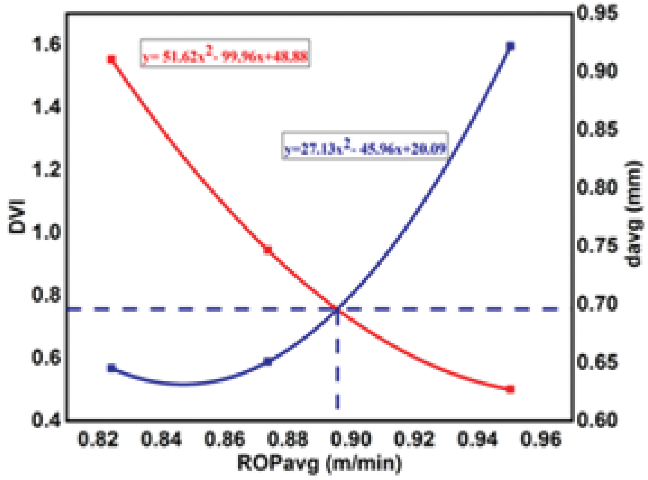


Fig 10 Correlation plot of ROP$_{avg}$ with DVI and d $_{avg}$

This suggests that the machine penetration rate decreases with a higher drill vibration index. At the same time, with a decrease in DVI, the average size of drill cuttings increases with an increase in ROP. Therefore, it can be summarized that the blast-hole drill machine yielding higher drill vibration index is more likely to give poor performance.

CONCLUSION

The particle size of drilled rocks was found to increase with an increase in the rate of penetration. Mean particle sizes of 0.63 mm, 0.71 mm, and 1.04 mm were found for the three increasing rotational speeds at 80, 85, and 90 rpm, respectively

The generation of vibration during rotary blast-hole drilling along the axial direction was observed to be higher in comparison to the lateral direction. Higher vibration generation along the axial direction was presumably due to the initial instability of drilling components during bit-rock interaction and inept control of operating variables by the operator during the drilling process. The maximum peak acceleration obtained was of the magnitude of 0.19 m/s^2 at 90 rpm.

Vibration generated showed a decreasing trend with an increase in pull-down force and torque at varying rotational speeds along with the corresponding increase in the rate of penetration. The average penetration rate varied from 0.82 to 0.95 m/min with resultant vibration magnitude from 0.05 to 0.17 m/s^2. The optimal operating condition was obtained at a pull-down force of 1560-1600N, torque at 2470-2500 Nm, and rotational speed at 85 rpm.

The drill vibration index (DVI) was found to vary from 0.50 to 1, with the average ROP ranging from 0.82 to 0.95 m/min. The drill machine with DVI=1 or above is found to have poor performance with higher vibration and production of more fine drill cuttings.

Based on the investigations a drill operational strategy has been prepared for quick appreciation of the outcomes in Fig.11.

ACKNOWLEDGEMENT

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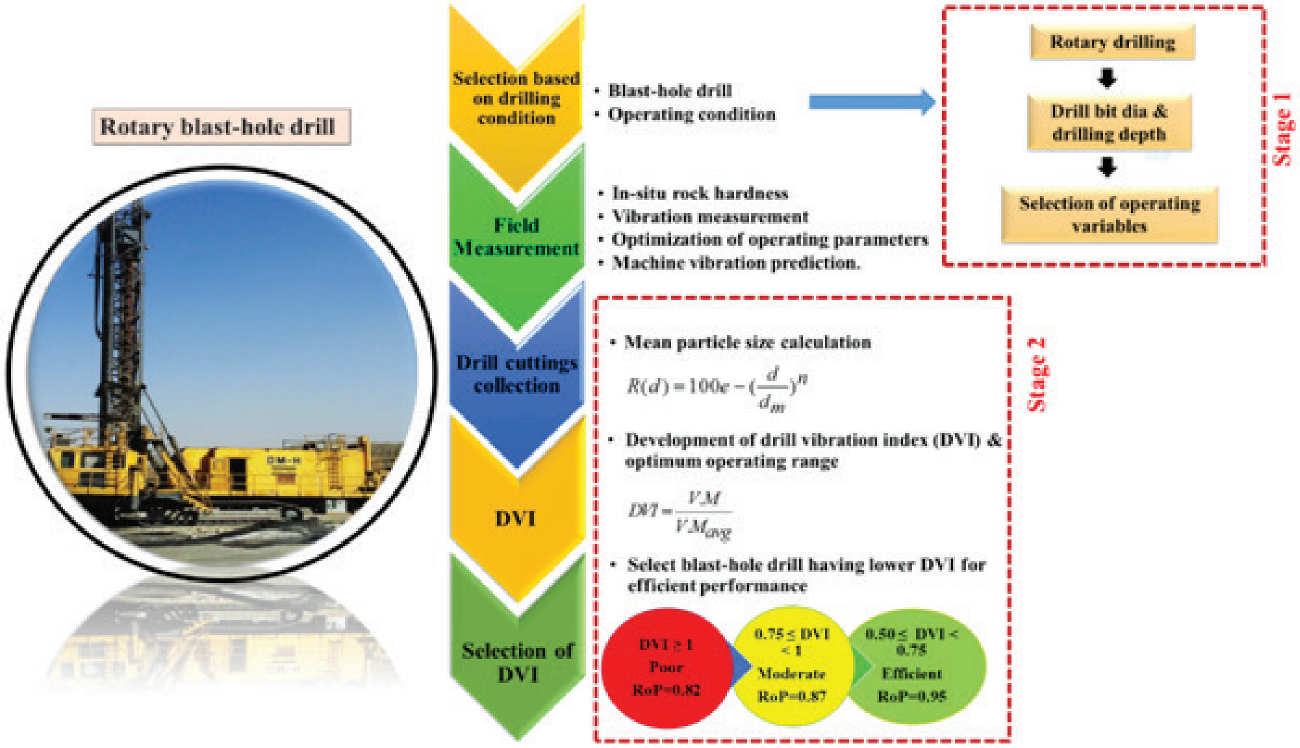

Fig 11. Rotary blast-hole drill operational strategy

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APPLIED MINERALOGICAL STUDIES ON AN IRON RICH MANGANESE ORE

D.S. Rao[1] and Sunil Kumar Tripathy[2]

ABSTRACT

The beneficiation processes for any mineral deposit are highly dependant on the mineralogical characteristics of ore. In the current research, a focus was made to understand an Indian manganese deposit's mineralogy through characterization. Different characterization viz, physical, chemical and mineralogical tools were used to understand the characteristics in the ore deposit. The automated mineral analysis was also used to understand the modal mineralogy and liberation pattern of the minerals in the ore. Pyrolusite and cryptomelane are the major manganese-bearing minerals present in the ore. Similarly, 39% of the ore is iron-bearing minerals in hematite, goethite and limonite. Different separation probe studies were attempted to visualize the separation using gravity and magnetic separation. It is concluded that gravity separation is not feasible, but two-stage magnetic separation can enhance this low-grade ores quality to 35.9% manganese with a recovery of 34.4% and manganese-to-iron of 1.7 from a feed assaying 27.6% manganese.

Keywords : Low grade manganese ore; characterization; mineralogy; beneficiation

Introduction

Manganese ore is an indispensable raw material for the steel industry, used in pig iron, steel, ferroalloys, and the foundry industry. The demand for manganese increases in parallel with the steel demand, whereas high-grade manganese ores are being depleted. There is also an upsurge in demand in other sectors, particularly on battery applications. The World Bank Group has also identified manganeseas an imperative element due to its wide application in evolving low-carbon technology and in technology-based mitigation scenarios, which ultimately helps to generate a low-carbon future(Hund *et al., n.d.).* Although many manganese occurrences are known, the limited size of the deposits and association of either silica, iron, or phosphorous above the specified limits makes them marginal to submarginal or low-grade ores. Hence, such deposits are not economically exploitable due to the low concentration of manganese or high amounts of either silica, iron, or phosphorous. Due to manganese formations' diversity and complexity, the impurities are many in number and complex in nature.Several Indian deposits have reported on the association of high iron, phosphorous as well as silica as impurity and few attempts were also made to understand the feasibility of separation(Acharya, 1994; Acharya et al., 1994; Mishra et al., 2011; Mohapatra et al., 1996; Singh et al., 2019; Tripathy et al., 2013, 2015).

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Thus, proper utilization of the available low-grade manganese ore resources is a significant challenge for the mining and mineral-based industries. However, the generation of large quantities of low-grade manganese ore as fines during mining and the size-grading of high-grade manganese ores have resulted in the accumulation of large amounts of inferior-quality ore that is being dumped at mine sites, resulting in space constraints and environmental problems(Mani and Subrahmanyam, 1984; Naik et al., 2005). Mineralogy is a fundamental characterization of such low-grade ore/waste dump material for a better utilization perspective. Several pieces of literature on the beneficiation of low-grade ore deposit through physical separation and flotation(Mehdilo et al., 2013; Singh et al., 2019; Srivani and Noothana, 2019; Tripathy et al., 2015). However, in the literature, it is evident that the mineralogy has not focussed in-depth to understand the separation feature.

In the present investigation, low-grade manganese ore from an Indian deposit is focused on understanding the mineralogy and possible way to enhance quality. A detailed mineralogical characterization in terms of physical, chemical, and mineralogical aspectsare discussed to analyze the separation's feasibility. Different mineral characterization tools were used to understand the low-grade deposit and attempted for beneficiation through gravity and magnetic separation.

2. Experimental studies

2.1. Manganese ore

Low-grade manganese fines from the Joda area, India was used for the present investigation. The as-received sample was dum fines during mining, and the size varies in a wider range up to a maximum size of 40 mm. Before characterization, the samples were thoroughly mixed and subjected to crushing to a particle size below 10 mm. The samples were collected from five different regions and designated as Sample 1-5. The as-received samples were mixed thoroughly and subjected tosampling for the detailed investigation. Few samples were collected as a lump to analyze the geochemistry characteristics.

2.2. Characterization studies

The particle size distribution (PSD) of the sample was measured in a laboratory sieve shaker. ICP-AES (Integra XL, I.R. Tech. Pvt. Ltd) was carried out for the elemental assays. The sample's apparent density was calculated using a gas pycnometer (Model No: Accu Pyc II 1340, manufactured by Micrometrics Ltd.) and the bulk density was measured by a Geopycanalyzer (Model No: Geo Pyc 1360, manufactured by Micrometrics Ltd) via measuring the displacement volume of the sample.Thermogravimetric analysis (TGA) test for the manganese ore was conducted using NETZSCH STA (supplied by NETZSCH-Gerätebau GmbH, Germany), which assists in demonstrating the thermal degradation profile. In this experiment, approximately 20 mg of sample was placed in an alumina crucible and subjected to the TGA analysis. Argon gas was used to purge the sample, and the sample was heated up to 1150°C (at a rate of 5°C/min).Magnetic susceptibility of the low-grade manganese ore fines is measured at room temperature (25°C) by using Magnetic Susceptibility Meter (Model No. KT-10); supplied by Terraplus, Canada. The grounded sample was measured ten times, and the average value is considered the magnetic susceptibility.

The mineral phase analysis was carried out by X-ray diffraction (XRD) supplied by PANanalytical B.V. (The Netherland). A representative mixed sample was crushed to a particle size below 1 mm, and subjected to moldingfor microscopic studies. The polished section was scanned under an automated mineral analyzer (MLA) to obtain the modal analysis as well as liberation pattern. The details of these procedures are given in earlier publications(Rath et al., 2018; Tripathy *et al., 2017).* Optical microscopic studies were carried out using a Leitz make an instrument to understand the textural properties of the sample. Sink and float studies were carried out to understand the density distribution in the sample. Heavy liquid separation studies were conducted by treating the bulk mixed samples in two different density liquids (bromo form and asdiodo methane), and the obtained results are considered for interpretation. Prior to treating samples in these liquids, the particle size has reduced to below 3mm.The heavy and light fractions were collected after washing them thoroughly with acetone and water. All the heavies and light fractions were weighed and were analyzed.

The grindability test was conducted for manganese samplesand the work indices were determined for the particle size of 150µm for each manganese ore sample(Bond, 1961; Casagrande et al., 2017; Deister, 1987; Yap, 1982). The work index (Wi) for grinding was then calculated based on equation 1.

$$\mathrm{Wi} = 1.1 * \frac{44.5}{\mathrm{P}_{\mathrm{i}}^{0.23}\mathrm{G}_{\mathrm{bp}}^{0.82}\left[\left(\frac{10}{\sqrt{\mathrm{P}_{80}}}\right)-\left(\frac{10}{\sqrt{\mathrm{F}_{80}}}\right)\right]} \text{........................}(1)$$

Where 'F' and 'P' indicates the 80% passing size (µm) of the new feed and the last three grinding cycles respectively; 'Pi' indicates the targeted size (i.e. 150µm) in the circuit, and 'Gbp' is the average quantity of undersize generated per mill revolution (g/rev) during the last three grinding cycles.

2.3. Magnetic separation studies

Dry magnetic separation studies were carried out using Permroll magnetic separator to study the separation feature. Size classification of the as-received sample subjected to Permroll magnetic separation by optimizing the separator's roll speed and the separated products were subjected to elemental analysis to visualize the separation. Similarly, manganese samples were subjected to a wet high-intensity magnetic separator (WHIMS) supplied by M/s. Box Mag Rapid, England. The magnetic intensity of the separator was varied by grid gaps and applied current. Prior to the magnetic separation, the sample was first conditioned for 10 minutes. After conditioning, the slurry was passed through the magnetic separator. The fraction that was retained in the grids is the magnetic fraction and the fraction collected at the bottom was the non-magnetic fraction. Both the magnetic and non-magnetic fraction was dried, weighed and analyzed to check the purity and recovery of the product. The bulk sample was subjected to crushing and grinding and 100% passed through 500, 210, 125 and 75 microns. Then all these samples of different ground were subjected to 5, 7.5, 10 and 12 amperes of current. Then from each sample magnetic as well as non-magnetic fractions were collected and weighed and subjected to elemental analysis.

3. Results and discussion

3.1. Particle size, density and chemical analysis

Particle size analysis was carried out in a set of sieves, and the findings are given in Figure 1. Figure 1 shows that all the samples received are identical in distribution with a variation of +10%. The particles of these samples are below 10mm. Also, it can be observed that 80% (by mass) of the samples are of the particle size in between 4 to 6mm. Similarly, chemical analysis of the samples was carried out and given in Table 1. Table 1 shows that maximum and minimum values for the manganese content were varied from 24.7% to 31.3% respectively, in all these samples. Similarly,the iron content of the low-grade manganese ore fines is varied from 16.2% to 33.1%. For better understanding, the range of the variation is given in terms of maximum, minimum and average values of all the radicals analyzed. It is observed that, out of these five, sample-C, and E, have manganese content more than the iron content, sample-A & B have more iron content than that of manganese. In comparison, sample-C has manganese content more than iron, but the silica content is more than iron.

To further understanding size-wise chemical analysis of these fines is shown in Figure 2. It is found that the manganese content is minimum at ultrafine size in all the deposits, which indicates the possibility of desliming to enhance the quality of these deposits.Further, all the samples collected from different mines are mixed at equal proportion and used for further test work. The particle size analysis and size-wise chemical analysis along with bulk elemental analysis after mixing is given in Table 2.

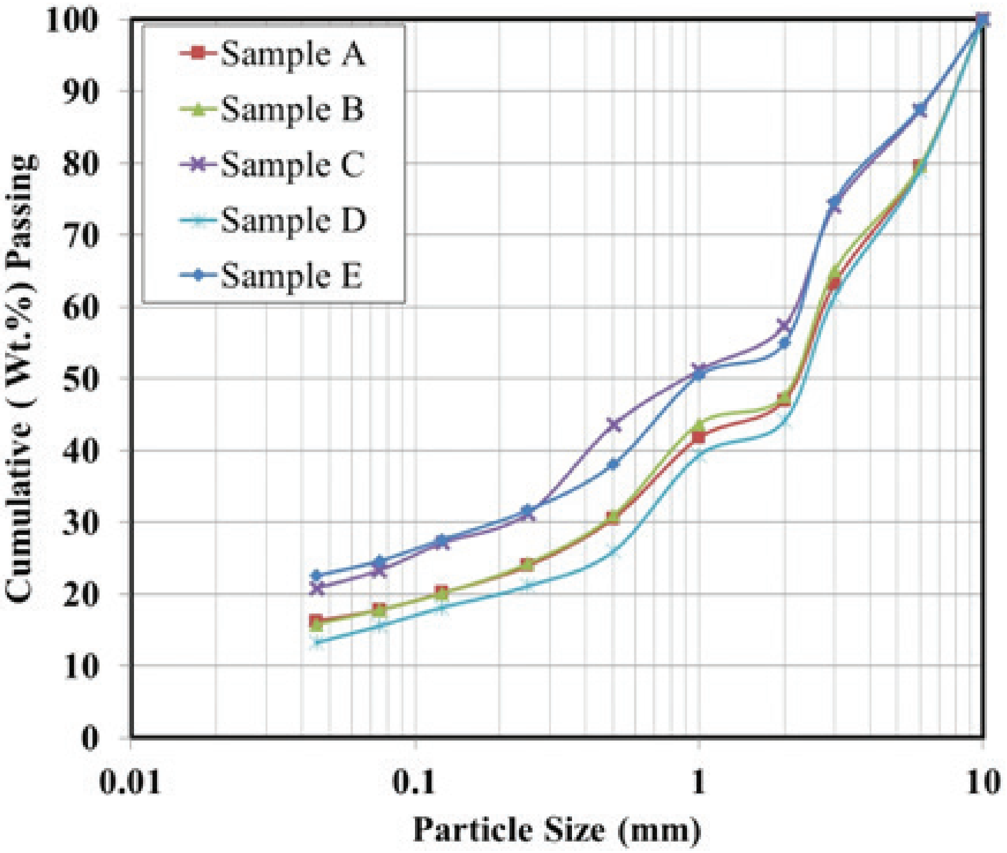


Figure 1: Particle size distribution of the as-received low-grade manganese ore fines.

Table 1: Chemical analysis of the low-grade manganese fines collected from different mines.

Source Details	Assay Value (%)						
	Mn	$Fe^{(t)}$	SiO_2	Al_2O_3	LOI	S	P
Sample A	24.7	25.5	12.4	6.2	9.0	0.004	0.039
Sample C	31.3	16.2	21.1	2.2	8.0	0.004	0.081
Sample B	26.0	33.1	4.7	3.9	8.6	0.004	0.047
Sample E	30.0	22.2	8.3	7.8	10.9	0.004	0.116
Sample D	26.1	25.3	8.2	8.5	10.5	0.003	0.093
Maximum Value	31.3	33.1	21.1	8.5	10.9	0.004	0.116
Minimum Value	24.7	16.2	4.7	2.2	8.0	0.003	0.039
Average Value	27.6	24.4	10.9	5.7	9.4	0.004	0.075

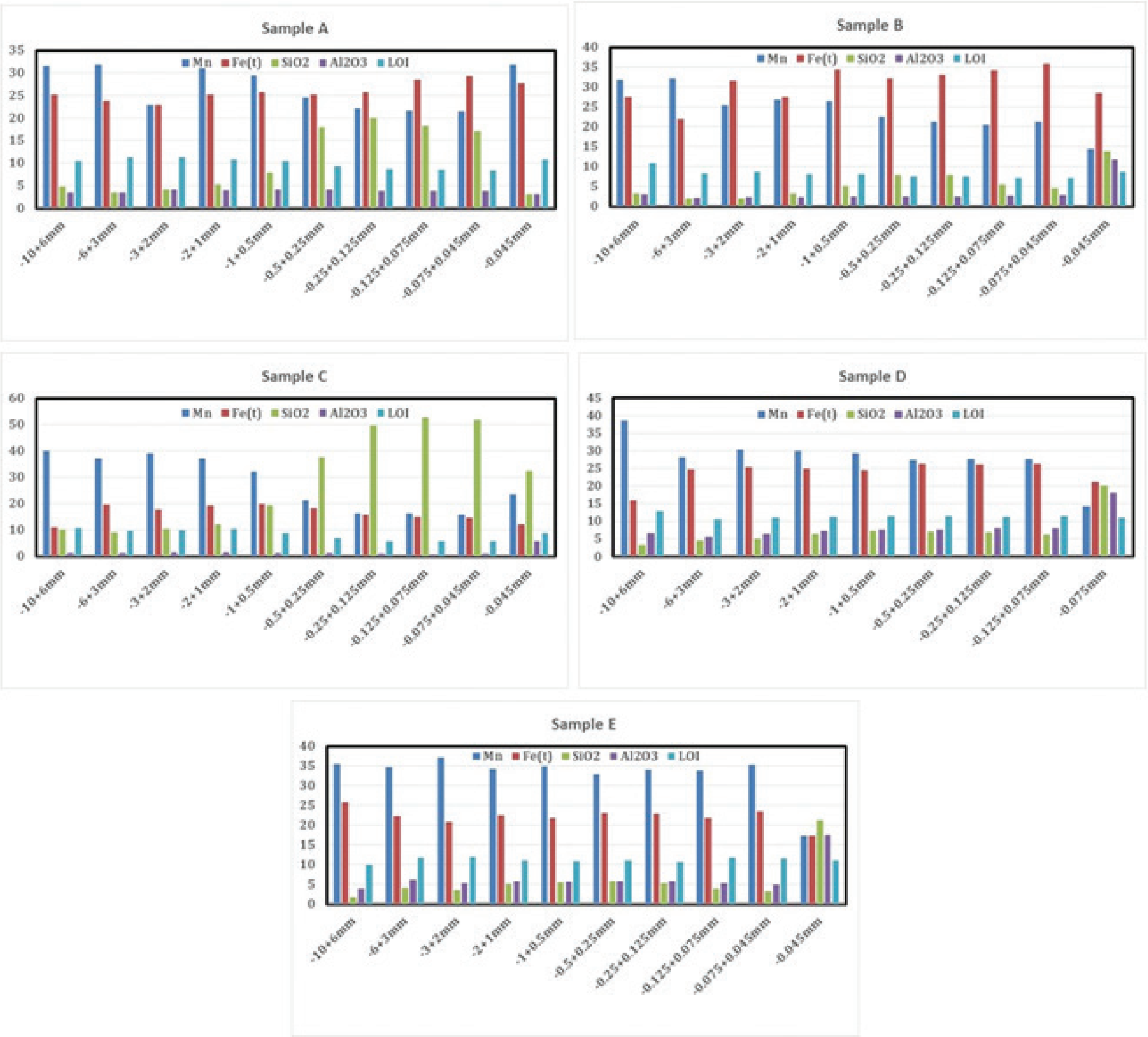


Figure 2 : Size-wise chemical analysis of the low-grade manganese fines

Table 2 : Particle size distribution and size-wise chemical analysis of the sample after mixing of different low-grade manganese ore.

Particle Size (mm)	Weight (%)	Assay Value (%)						
		Mn	Fe$^{(t)}$	SiO_2	Al_2O_3	LOI	P	S
10 + 6	15.6	32.4	26.4	1.7	3.4	10.9	0.120	0.002
-6+3	14.9	29.7	26.2	5.5	3.9	11.2	0.130	0.003
-3+2	16.4	33.2	24.0	2.7	3.7	11.4	0.120	0.004
-2+1	6.5	31.5	25.0	6.2	3.9	11.5	0.090	0.003
-1+0.5	12.1	31.5	26.2	7.7	4.0	10.1	0.090	0.003
--0.5+0.25	6.5	26.8	26.6	12.5	4.1	8.6	0.081	0.006
-0.25+0.125	4.1	24.1	26.3	16.7	4.0	9.1	0.080	0.003
-0.125+0.075	2.4	23.7	26.2	17.6	4.1	8.9	0.080	0.003
-0.075+0.045	2.1	23.3	25.6	17.9	3.8	8.9	0.070	0.004
-0.045	19.5	17.7	21.9	20.7	13.5	10.1	0.060	0.004

The density of the manganese fines was determined by using a helium Pycnometer, and the results are mentioned in Table 3. Table 3 shows that the density of the manganese fines varied from 4.14 to 4.59 g/cc. Further, the samples were mixed, and the density of this mixed sample was determined, and the reported value is 4.25 g/cc. Similarly, the bulk density of the samples was measured and found that the values are varying in between 2.31 to 2.67 g/cc.

Table 3: Particle density and bulk density of the low-grade manganese fines.

Source Details	Apparent density (g/cc)	Bulk density (g/cc)
Sample A	4.31	2.39
Sample B	4.59	2.67
Sample C	4.14	2.31
Sample D	4.25	2.38
Sample E	4.32	2.35
Mixed sample	4.25	2.33

3.2. Magnetic Susceptibility Analysis

Magnetic susceptibility of the low-grade manganese ore fines is measured using Magnetic Susceptibility Meter, and the results are given in Table 4. From Table 4, it is found that the magnetic susceptibility value is varied between 0.63 to 1.13X10-3m3/kg. The range of the variation (measured ten different readings) is given in terms of maximum, minimum and average values of magnetic susceptibility of all the fines calculated. Similarly, after mixing all the samples, the bulk sample was analyzed for the magnetic susceptibility and value of the magnetic susceptibility of 0.79X10-3m3/kg. It is confirmed that the sample contains par-magnetic minerals, including manganese bearing minerals. However, the separation under the magnetic field will be influenced by the difference between the manganese bearing minerals and others.

Table 4 : Magnetic susceptibility values of the low-grade manganese ore fines.

Sample Details	Magnetic susceptibility (10-3) m3/kg		
	Maximum	Minimum	Average
Sample A	0.87	0.76	0.80
Sample B	2.02	0.57	1.13
Sample C	0.70	0.53	0.63
Sample D	1.07	0.65	0.86
Sample E	1.06	0.76	0.94

3.3. Physical characteristics

Hand specimen examination showed that the ore submitted for testing varied widely in its physical nature and mineralogical composition. Samples varied from very hard siliceous material to soft friable earthy material. Silicification in the form of clay was evident in some specimens. The grain size in the fragments examined was coarse to fine and uneven, and intergrowths between the constituent minerals very complex were commonly observed in the hand specimens. These are spongy-cavernous, friable-biscuity, massive botryoidal types. These different types of ores are closely interrelated and grade into one another.A few hand specimens were collected from other geographical locations, various mines. Although on the first inspection, many manganese minerals appeared to be in grains of relatively large size (Figure 3). From the hand specimen and physical look, it was evident that a high recovery of manganese in a concentrate meeting market specifications/demand in terms of manganese content could not be expected or achieved just by physical beneficiation for removal of silica.

The megascopic studies indicated that the samples show silicates (both quartz and clay) as patches of wide different sizes and shapes (Figure 3).Various shapes and sizes of clay and quartz (Figure 3 a to d) within the manganese ores. Intricate association of clay (white) and goethite patches within manganese ores. Goethite and manganese ore containing voids giving rise to porous structure.Patches of ocherous goethite and clay within manganese ores. These manganese ores show oolitic/botryoidal texture (Figure 3e). Limonitic patches (brown-red) are also observed within the clayey matrix of manganese ores (Figure 3f).

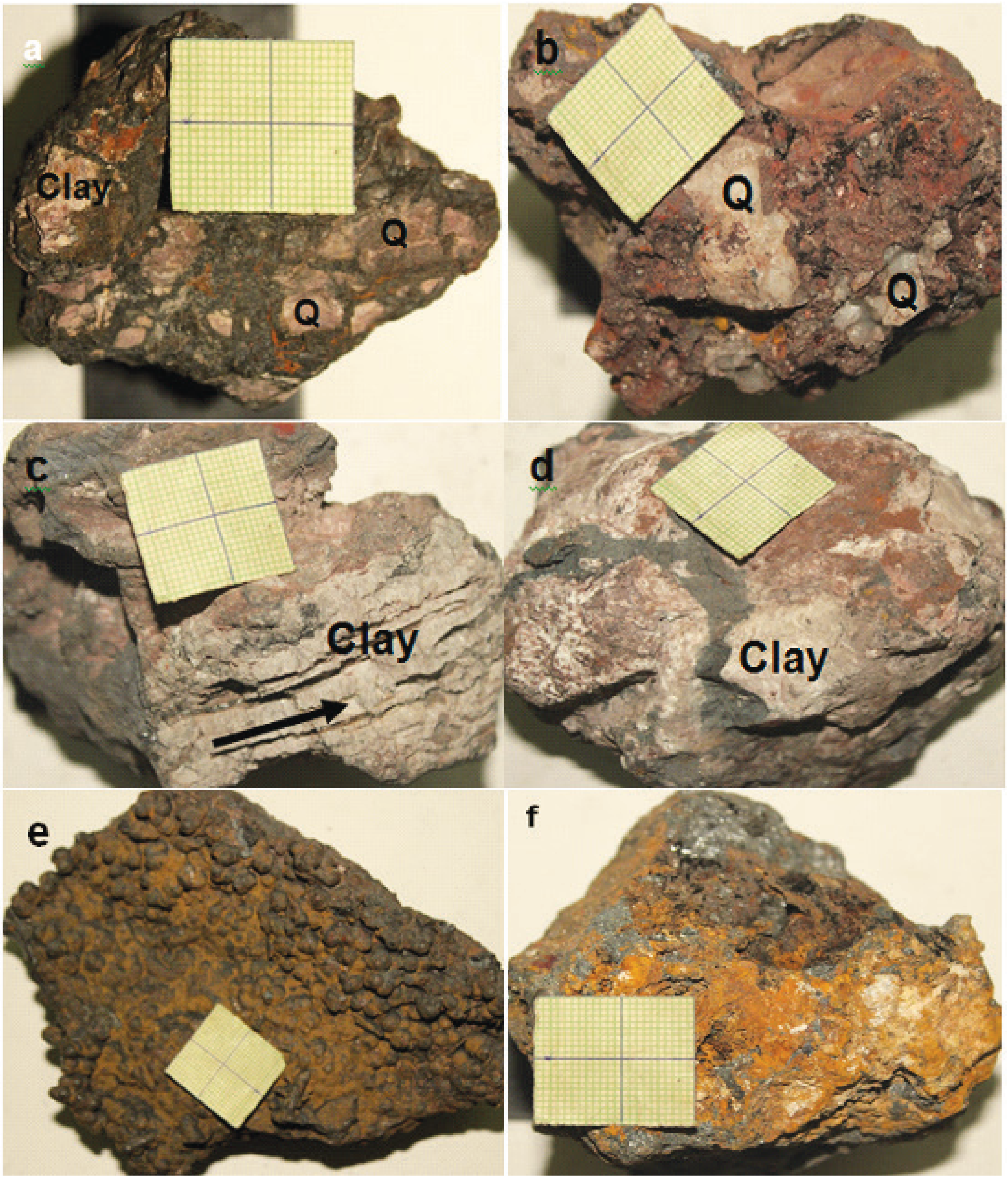


Figure 3. Hand specimen photomicrographs. (a) Quartz (Q) and clay (C) patches in manganese ores. (b) Numerous shapes and sizes of quartz (Q) crystals in manganese ores. (c) Clay patches along a linear direction in manganese ores. (d) Patches of clay within the manganese ores. (e) Botryoidal/nodular manganese oxides. (f) Limonitic patches within the manganese ores.

3.4. Geochemical characteristics

A few handpicked samples were subjected to chemical analyses for their total manganese, total iron, silica, alumina, and Loss on Ignition (LOI) values based on visual observation. Wide variation (Table 5) in manganese, iron contents observed. Some of the siliceous manganese ores, containing high silica are very poor in iron content. In contrast, some of the samples indicated that they are manganese ores with insignificant iron and silica content. Based on the analyses, it can be predicted that the manganese ore from this mine belongs to the following categories (i) Manganese ore (ii) Iron-rich/ferruginous manganese ore(iii) Silica-rich/siliceous manganese ore. It can be inferred that the samples are iron-rich manganese ores or ferruginous manganese ores and need beneficiation for utilization. The chemical characteristics, indicating iron-rich manganese ores, confirm the microscopic findings and the presence of high amounts of goethite in the sample.

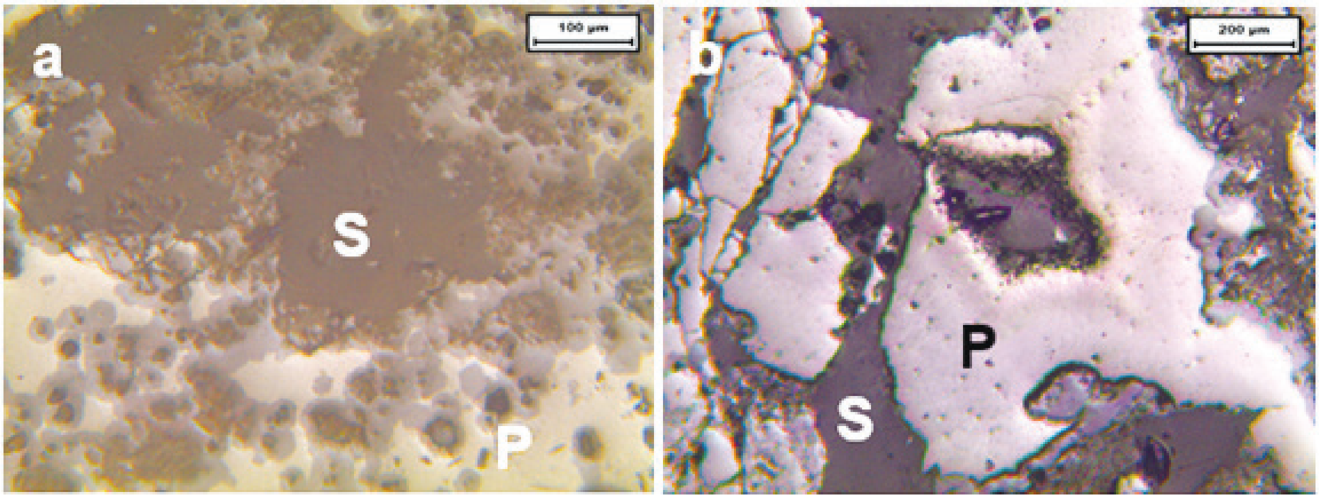
Table 5 : Chemical analyses of the handpicked samples

Sample number	Mn(t)	$Fe_{(t)}$	SiO_2	Al_2O_3	LOI	Remarks on type of ore types
1	59.18	4.33	0.45	2.13	13.41	Manganese ore
2	55.81	7.17	0.70	2.50	13.03	Manganese ore
3	41.86	19.33	0.84	4.69	11.75	Iron rich/ferruginous manganese ore
4	33.97	21.26	0.14	4.55	15.29	Iron rich/ferruginous manganese ore
5	17.33	37.23	0.39	6.25	8.36	Manganese rich/ manganiferous iron ore
6	67.29	0.49	0.34	0.48	10.21	Manganese ore
7	62.28	1.53	1.11	2.91	12.24	Manganese ore
8	60.73	1.17	1.06	4.01	13.56	Manganese ore
9	56.99	4.04	0.09	5.79	13.57	Manganese ore
10	24.79	36.44	0.76	3.00	10.74	Iron rich/ferruginous manganese ore
11	19.07	31.03	2.48	14.53	12.55	Iron rich/ferruginous manganese ore
12	66.28	0.08	0.64	0.37	9.64	Manganese ore
13	60.17	1.09	0.13	1.98	10.77	Manganese ore
14	53.05	6.71	1.83	3.86	10.75	Manganese ore
15	52.60	8.04	0.50	3.06	11.72	Manganese ore
16	26.48	2.73	53.42	0.84	5.22	Siliceous Manganese ore
17	62.45	0.50	0.84	0.42	12.13	Manganese ore
18	43.14	17.13	1.85	2.60	12.55	Iron rich/ferruginous manganese ore
19	23.39	1.54	61.45	0.55	5.04	Siliceous manganese ore
20	22.57	25.03	8.37	10.15	14.28	Iron rich/ferruginous manganese ore
21	59.63	2.46	0.89	2.21	12.26	Manganese ore
22	55.40	4.95	0.22	0.96	13.60	Manganese ore
23	55.00	6.52	0.07	1.35	14.07	Manganese ore
24	37.21	22.07	1.90	0.93	13.89	Iron rich/ferruginous manganese ore
25	28.95	26.78	2.02	5.72	14.47	Iron rich/ferruginous manganese ore
26	20.84	33.14	6.70	8.00	10.73	Manganese rich/manganiferous iron ore

3.5. Mineralogical characteristics using an optical microscope

Handpicked samples were made polished sections following conventional grinding and polishing methods. Then the polish sections were studied under a reflected light microscope for phase identification. The iron-rich manganese oxide ores in Joda, Odisha consist of the manganese minerals: cryptomelane, romanechite, pyrolusite, and lithiophorite and the iron minerals: goethite and hematite. A mixed Mn-Fe-Al phase is invariably present. Quartz, kaolinite, and zircon are the silicate gangue minerals in the ore (Figures 4-6). The manganese minerals mostly show colloform, mammillary, vein filled, fibrous and other replacement textures.

Various shapes and sizes of pyrolusite crystals within the silicates and vice-versa (Figure 4). Cryptomelane and romanechiteare enclosed and enclosing the clayey matrix. At times pyrolusite and romanechiteare enclosed within goethite.Wide different sizes of silicate (Si) minerals present within the goethite, pyrolusite and cryptomelane. Lithiophorite occurs as fine fibrous along with clay and as granules along with Pyrolusite material. Occasionally lithiophorite contains islands of silicates (Figure 5). Goethite (Figure 6), in these samples, occur as (a) massive mass, (b) pores, cavity, and fracture filling, (c) thick and thin bands colloform bands, pisoids, and botryoids occasionally parallel with the bandings with pyrolusite,and cryptomelane. Colloform bands of ochreous and vitreous goethitealso occur in these ores (Figure 5).Thepresence of ochreous and vitreous goethite, having a varying chemical composition, has also been reported in this sector's iron ores (Das *et al., 2010).* In general, from ore microscopic studies, it can be concluded that quartz, clay the silicate gangue minerals; hematite and goethite are the iron phase minerals in the sample, present in a very complex and complicated interlocking way with the manganese phases like pyrolusite, cryptomelane, romanechiteand lithiophorite. From the microscopic studies, it also can be said the quantitative amounts of iron phases present are more or less the same as manganese phases. From the microscopic studies, it can also be predicted that the liberation of iron phases from the sample is very difficult because of their fine sizes and intricate textural associations. Any attempt of physical beneficiation (conventional techniques of gravity or magnetic separation)for these iron-rich manganese ores, the Mn/Fe cannot be improved.



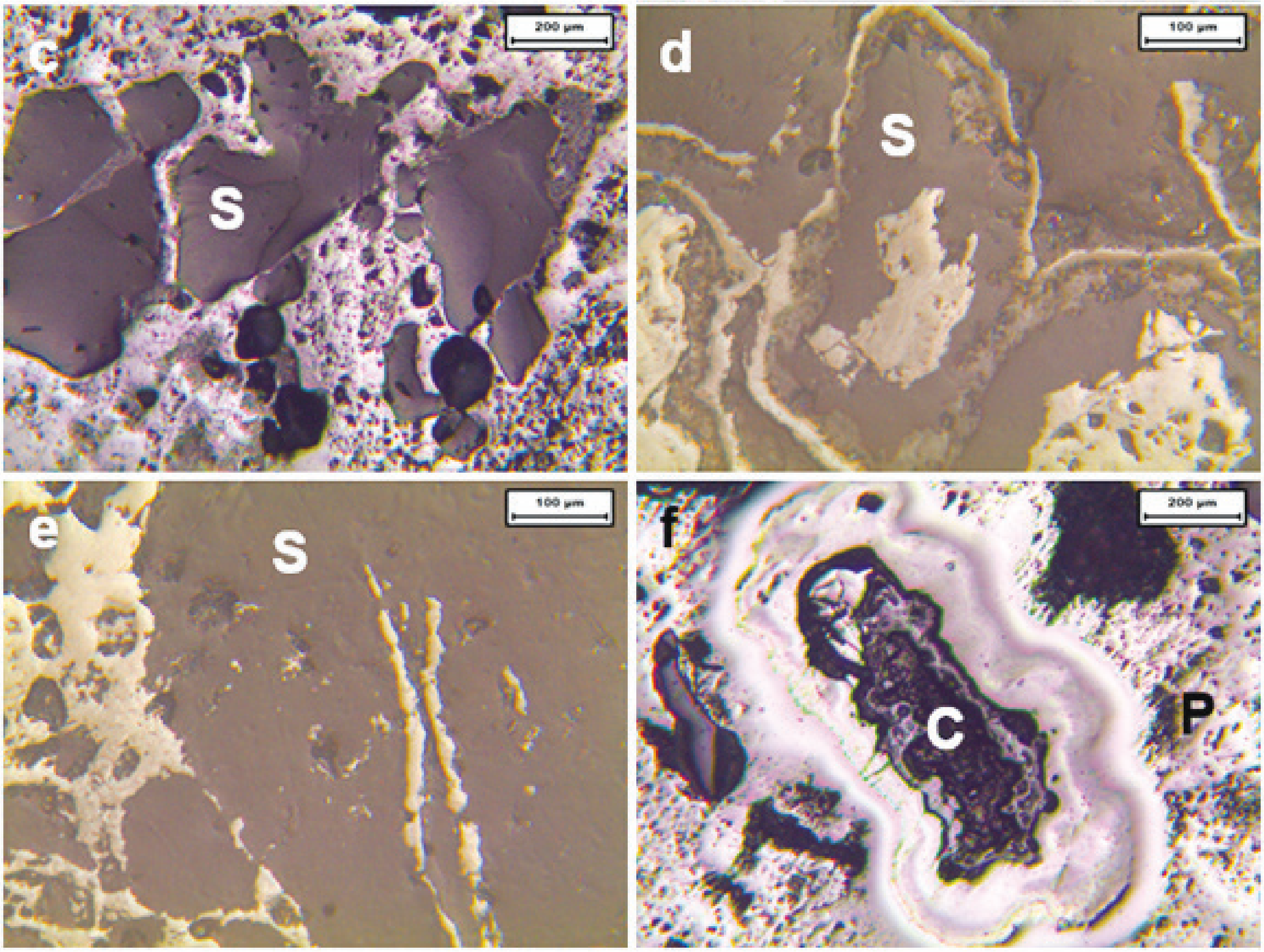
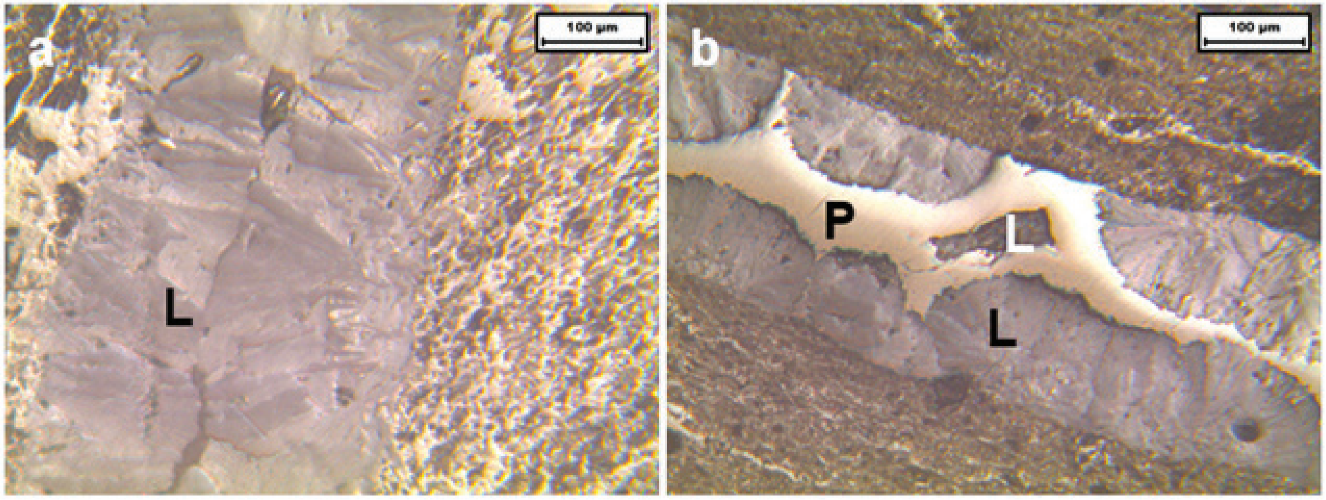


Figure 4.(a) Various shapes and sizes of silicates contained within oolitic goethite and pyrolusite (P). (b) Pyrolusite (P) contains and contained within the silicates (S). (c) Numerous shapes and sizes of silicates within cryptomelane (white). (d) Patches of pyrolusite (white) contained as islands within the silicates. (e) Elongated shaped pyrolusite (white) within in the silicates. (f) Clayey (C) patches within the colloform of bands of pyrolusite, cryptomelane and goethite. Reflected light photomicrographs.



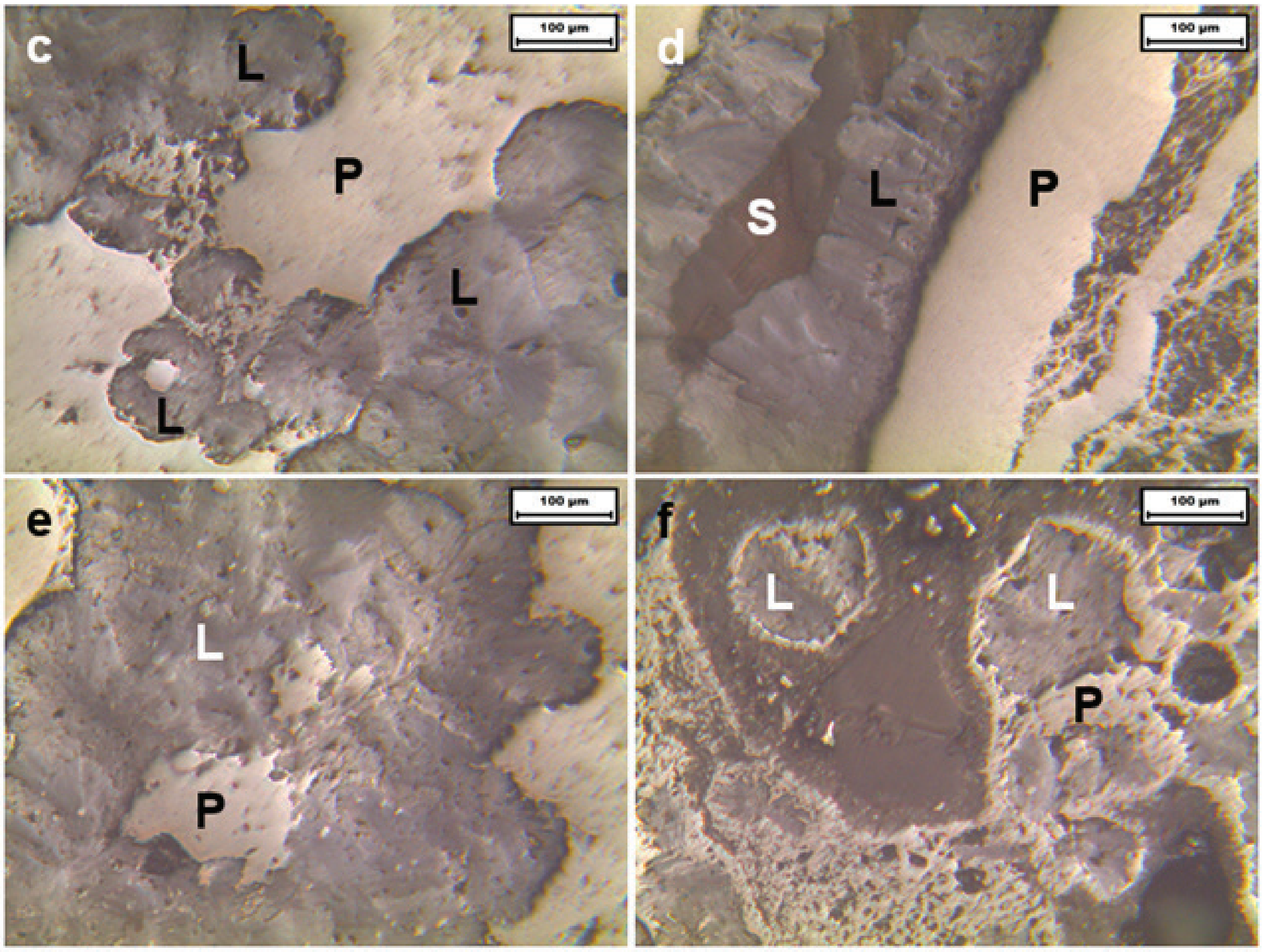
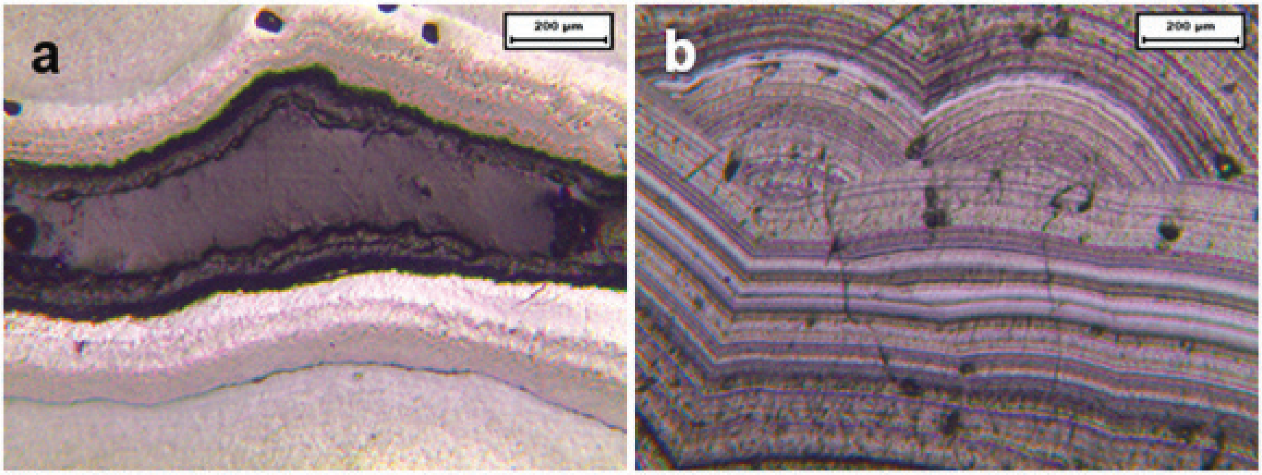


Figure 5.(a) Lath shaped lithiophorite (L) within the pyrolusite and cryptomelane (b) Lithiophorite (L) contains islands of pyrolusite (P) and contained within the pyrolusite (P). (c) Rounded shaped (oolitic types) of lithiophorite (L) contains islands of pyrolusite and contained within the pyrolusite. (d) Elongated silicate (S) grains within lithiophorite (L) bands contained within pyrolusite bands. (e) lithiophorite (L) contains islands of pyrolusite and contained within the pyrolusite (f) Rounded shaped (oolitic types) of lithiophorite (L) contains islands of pyrolusite and contained within the silicates. Reflected light photomicrographs.



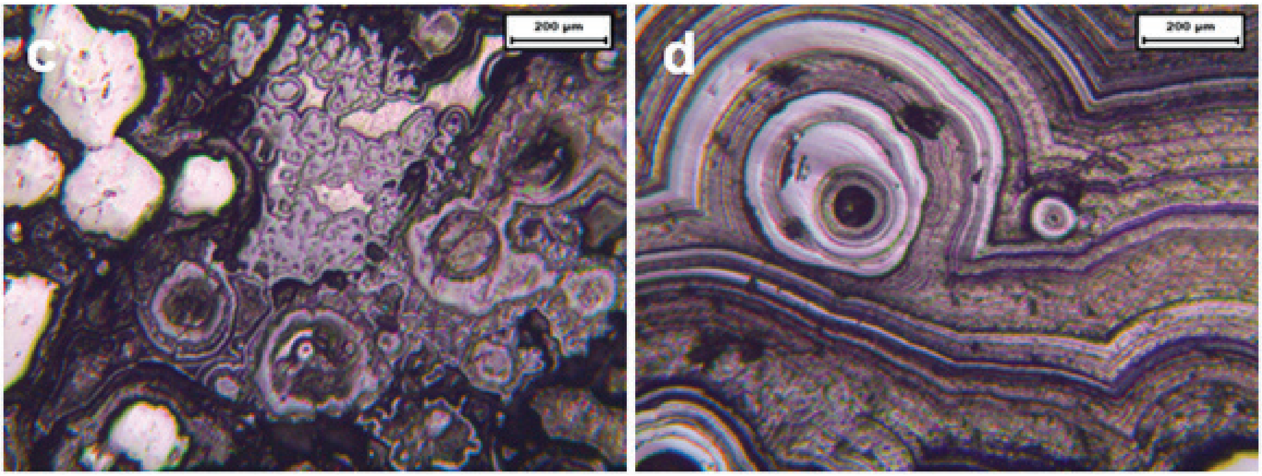


Figure 6: (a) Colloform textures of pyrolusite and cryptomelane enclosing islands of silicate minerals. (b) Colloform texture of vitreous and ochreous goethite along with bands of oxy-hydroxides of iron and manganese. (c) Oolities of goethite along with vitreous goethite and pyrolusite (white) (d) oolites containing clayey materials and colloform texture of vitreous and ochreous goethite along with bands of oxy-hydroxides of iron and manganese.Reflected light photomicrographs.

3.6. Mineralogical characteristics using the electron microscope

Prior to the mineral analysis by using the automated mineral analyzer, the elemental analysis was carried out for different mineral grains by using SEM-EDX and images along with micro-analysis are mentioned for better understanding. Mineral chemistry can help indentify mineral phases and indicate the association of valuable and harmful trace elements. Selected minerals in the Joda area manganese ores were subjected to SEM-EDS study and depicted in Figure 7 and Table 6. Figure 7 illustrates the back-scattered images of a polished section. The analyses, individual numbers on the figure, are reported along with their mineralogical names in Table 6. Table 6 indicated that pyrolusite, romanechite; Iseite; hematite; cryptomelane; Fe-cryptomelane, and lithiophorite are predominant in this analysed section. The cryptomelane grains indicated that they are essentially potassium-bearing manganese oxide phases. K_2O >BaO distinguishes cryptomelane from romanechite. The SEM-EDS analyses revealed that the manganese phases contain iron within them and similarly iron phases contain some quantities of manganese within them. It is clearly observed that the hematite, occurs along with and within the pyrolusite, cryptomelane as well as romanechite manganese oxide phases, as islands having extremely fine size crystals (to the level of 10μm) indicating that these cannot be separated out by physical beneficiation methods. Some cryptomelane contains significant amounts of iron oxide along with them leading them to be iron rich cryptomelane.

Iseite is the mineral species that is reported here for the first time. Molybdenum does not occur in nature in its native state. It is only found chemically combined with other elements, particularly sulphur and has been reported as molybdenite (MoS2; is the principal ore of molybdenum) in porphyry sulphide deposits. Iseite, a new mineral that is a Mn-Mo dominant oxide mineral analogue of kamiokite, is found in the ferromanganese ores of Joda. Here, the authors describe the mineral, Iseite found along with the manganese minerals of Joda sector. Iseite is the mineral species that includes both Mn and Mo as essential constituents. Among naturally occurring molybdenum oxide minerals, only the Fe mineral species, kamiokite ($Fe_2Mo_3O_8$), is widely recognized(Johan and Picot, 1986; Nishio-Hamane *et al., 2013).* Recently, the Mg analogue of kamiokite, $Mg_2Mo_3O_8$, was reported from the Allende meteorite. The Mn analogue of kamiokite, that is

$Mn_2Mo_3O_8$, named iseite have been reported by Nishio-Hamane et al., and has been approved by International Mineralogical Association(Nishio-Hamane *et al., 2013).*

3.7. Mineral analysis using an automated mineral analyser

For the present study, all the iron oxide phases were considered one phase particles as iron oxide minerals and all kinds of manganese minerals were considered one manganese oxide phases. All other oxides and sulphide and silicate were kept as considered an individual mineral phase system. The modal mineralogy of these grouping minerals is shown in Figure 8. The quantitative mineralogical data shown in Figure reveal that the iron oxide phases (hematite, goethite and limonite) are highest in abundance (39.71%) followed by the manganese oxide

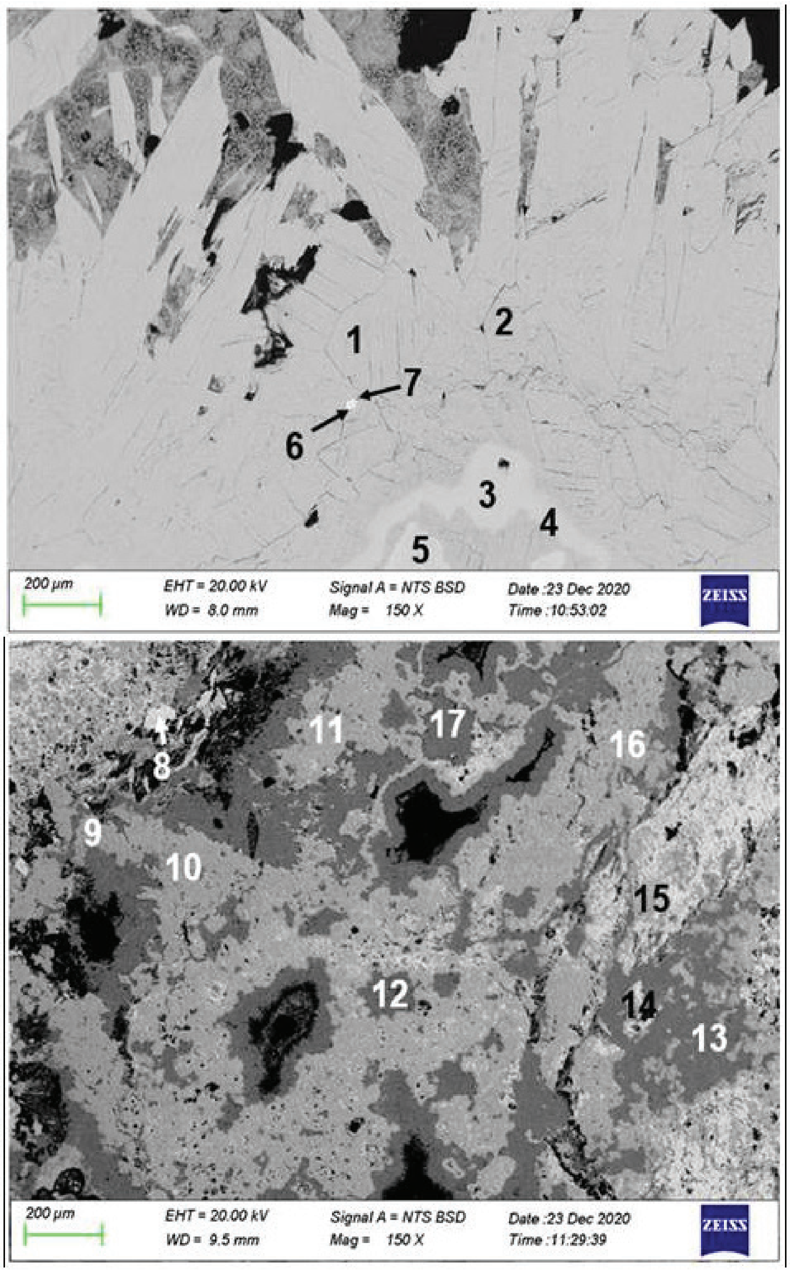


Figure 7. BSE electron image of manganese sample.

Table 6. Elemental analysis derived from EDS of the selected points in SEM.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
O	27.80	25.27	27.33	28.16	27.61	28.89	35.12	24.93	33.49	33.36	33.29	36.08	39.32	33.65	33.23	33.49	40.61
Na	1.45	1.75	0.47	0.37	0.70	1.88	2.53	0.04	0.03	0.19	0.46	0.09	0.48	0.30	0.08	0.04	0.19
Mg	0.45	0.56	0.15	0.04	0.18	0.12	0.20	0.24	0.32	0.43	0.12	0.62	0.71	0.53	0.34	0.21	0.39
Al	1.09	2.82	0.31	0.48	0.33	0.27	0.20	0.25	0.40	0.70	0.57	14.32	13.61	0.98	0.97	0.50	13.96
Si	1.77	0.27	0.04	0.01	0.04	0.52	0.49	0.25	0.41	0.32	0.41	0.68	0.19	0.47	0.23	0.42	0.31
P	0.09	0.15	0.03	ND	0.01	1.05	0.97	0.00	0.22	0.14	0.19	0.15	0.08	0.11	0.17	0.19	0.08
S	ND	ND	ND	ND	ND	1.69	0.75	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
K	0.18	3.37	1.80	1.60	1.17	0.24	0.35	0.12	1.99	2.26	2.20	0.19	0.11	1.97	1.77	1.98	0.16
Ca	0.28	0.24	0.55	0.05	0.14	0.14	0.20	0.19	0.25	0.21	0.23	0.23	0.16	0.27	0.14	0.20	0.14
Ba	0.45	0.55	3.03	2.81	4.24	0.61	0.80	0.96	0.59	0.30	0.29	0.57	0.73	0.57	0.46	0.70	0.31
Ti	0.02	0.03	ND	ND	ND	ND	0.04	0.06	0.10	0.00	0.00	0.03	0.01	0.07	0.00	0.00	0.06
Mn	64.45	63.30	63.72	65.19	63.55	10.15	7.05	2.04	58.21	58.75	58.40	38.87	37.85	53.41	51.70	52.52	38.39
Fe	1.96	1.69	2.58	1.28	2.03	1.15	0.93	68.29	1.61	1.09	1.72	1.91	1.52	5.55	6.06	7.02	1.24
Mo	ND	ND	ND	ND	ND	49.83	48.06	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Co	Nd	Nd	Nd	Nd	Nd	0.67	0.49	0.79	0.61	0.56	0.53	1.27	1.28	0.60	1.40	0.59	1.54
Ni	Nd	Nd	Nd	Nd	Nd	1.10	0.68	0.46	0.38	0.44	0.38	1.51	1.00	0.32	1.09	0.51	1.53
Cu	Nd	Nd	Nd	Nd	Nd	0.93	0.53	0.42	0.23	0.30	0.24	1.09	1.63	0.40	0.62	0.51	0.33
Zn	Nd	Nd	Nd	Nd	Nd	0.76	0.59	0.90	1.12	0.85	0.95	2.15	1.13	0.74	1.67	1.11	0.55

Remarks: Point 1 & 2- pyrolusite; 3-5- Romanechite; 6 & 7- Iseite; 8-hematite; 9-11-cryptomelane;14-16-Fe-cryptomelane; 12,13 &17-lithiophorite; ND=Not detected, Nd= not determined

(38.78%) minerals (pyrolusite,crypromelane andlithophorite). Manganese silicates (garnets) constitute the highest (10.46%) among silicates, followed by quartz (5.96%). The automated mineral analyzer also reports minor amounts of muscovite, kaolinite, and ilmenite and barite traces in this sample. The liberation characteristics of these groping mineral phases Are shown in Figure 9. The liberation data shown in Figure 9 indicated that 25.02% out of the 38.78% Mn minerals are liberated completely at particle size below 1mm while 15.53% of the 39.71%iron oxide phases are liberated. Further, the data indicate that the degree of liberation of different minerals increases order with a decrease in the particle size until the sizefraction -75+38µm. These results elucidate the pattern of locking various phases in a very complex way and indicate that physical beneficiation may not be practically possible to attain better grades and acceptable recovery.

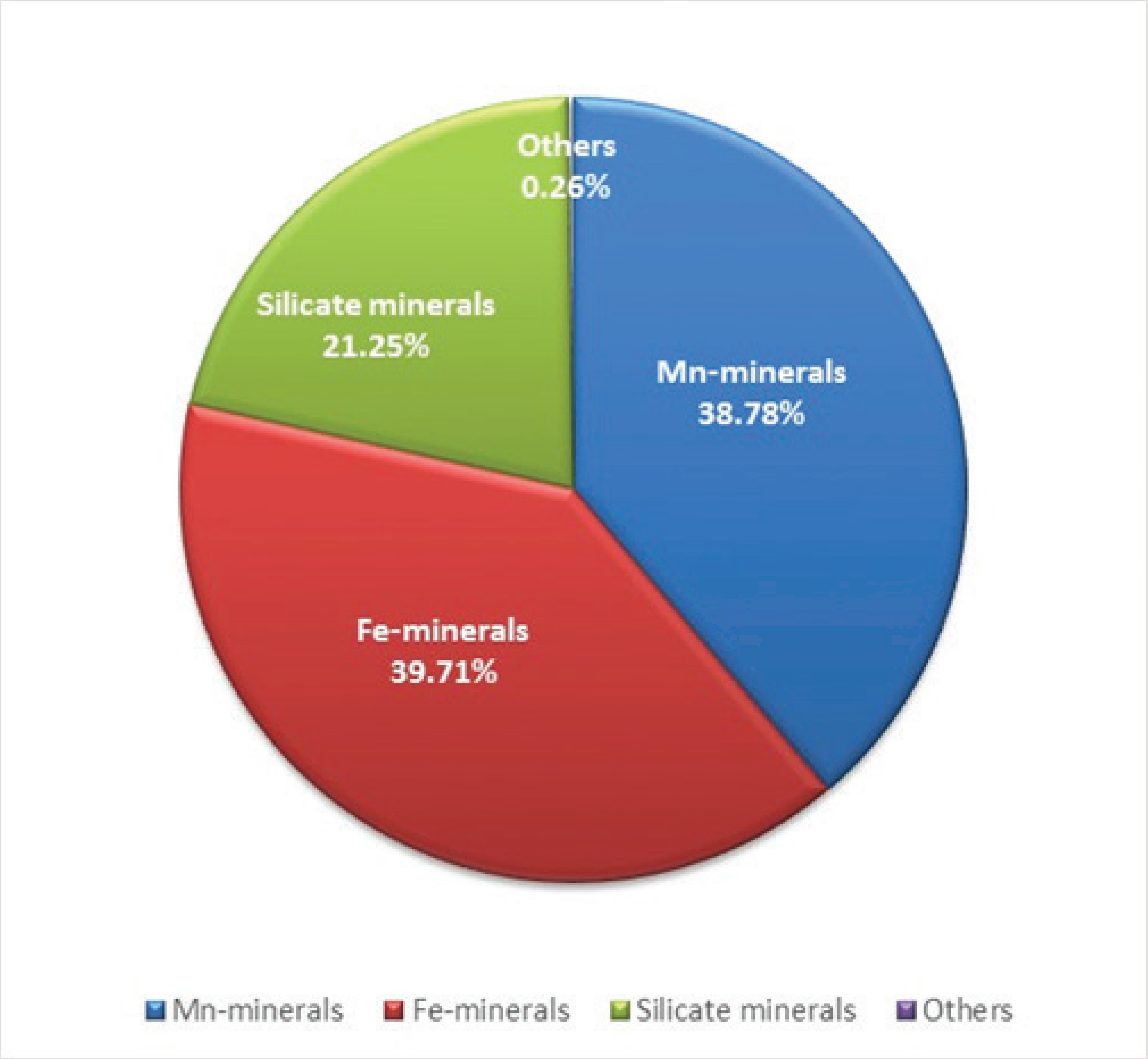


Figure 8. Modal mineralogy of the mixed manganese ore sample

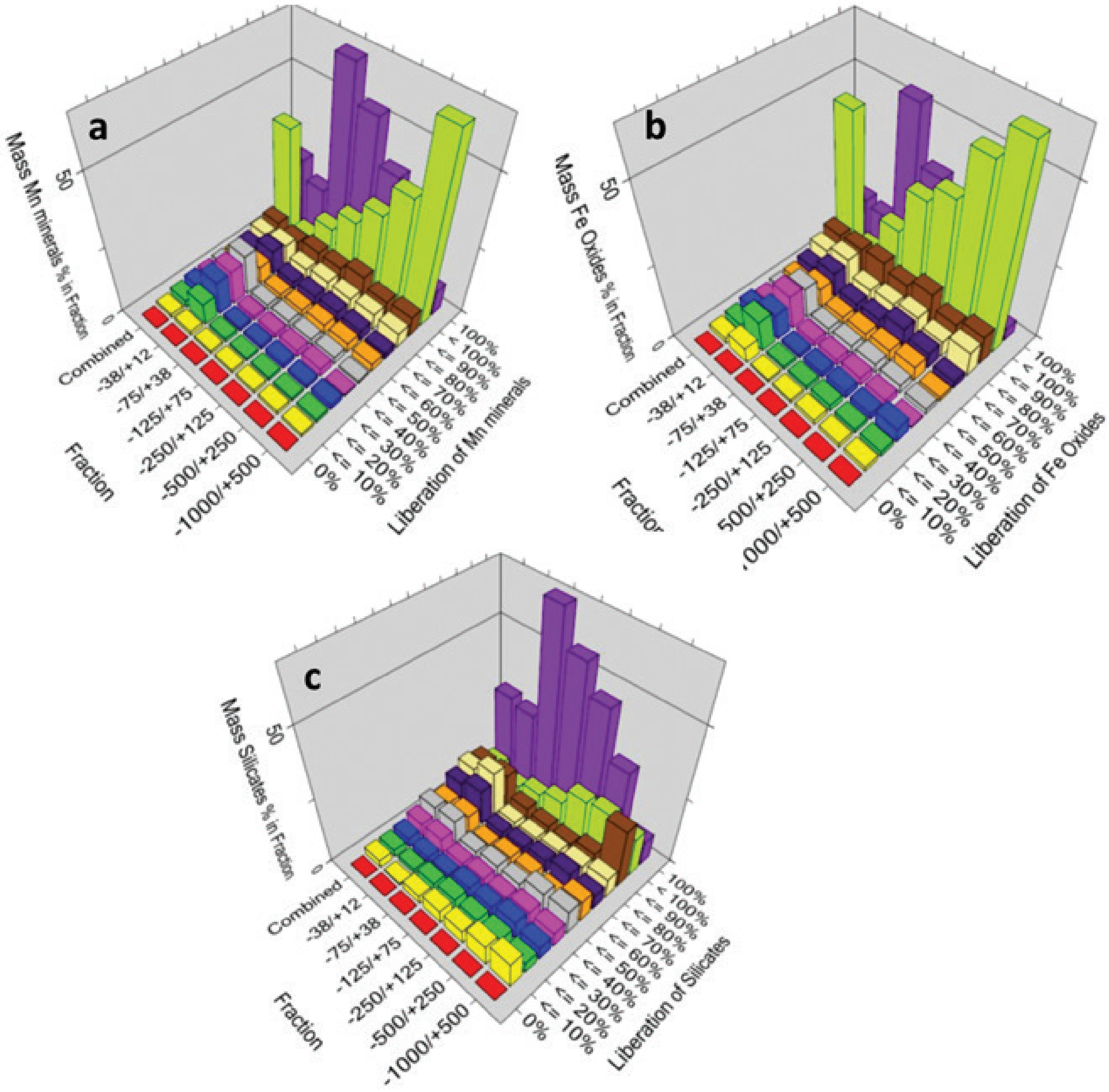


Figure 9. Liberation characteristics of grouping mineral phases (presented with respect to individual mass)

Heavy liquid separation

Sink and float studies were also carried out for the bulk sample after grinding the sample and passing the same through -3mm sieve. The sink and float studies were carried out with bromoform, and MI solutions and the details are reported in Table 7. The heavy and light fractions were collected after washing them thoroughly with acetone and water. All the heavies and light fractions were weighed and were analyzed.

Heavy liquid separation studies were conducted by treating the bulk mixed samples in two different density liquids (bromoform and di-io-do methane). The obtained results are given in Table 7. Prior to treating these liquids in this, the particle size has reduced to -3mm. Table 7 shows 7% (by wt.) materials having a particle density below 3.3 g/cc. This indicates the minimum amount of liberated low-density gangue minerals and abundance of near density minerals of pyrolusite. Also, the separation is ineffective as the density of manganese and iron bearing minerals is closed to each other.

Table 7. Heavy liquid separation of mixed low grade manganese ore fines.

Density (g/cc)	Product	Wt. (%)	Assay Value (%)				
			Mn	$Fe^{(t)}$	SiO_2	Al_2O_3	LOI
2.8	Float	4.3	17.5	14.5	32.6	8.2	10.6
		Sink	95.7	28.1	26.6	9.6	5.5
3.3	Float	7	16.1	13.7	34.8	9.3	10.0
	Sink	93	28.6	27.0	8.8	5.3	8.9

(LOI- Loss on ignition; Fe(t)-Totoaliron)

3.9. Thermo-gravimetric Analysis

Thermo-gravimetric analysis or thermal gravimetric analysis (TGA) is a type of testing performed on samples that determines the change in weight in relation to change in temperature was carried out and shown in Figure 10. From the weight loss graph, the presence of different hydroxide minerals can be confirmed. As the hydroxide minerals such as goethite, kaolinite present in the sample, it is necessary to establish and quantify their content, which guides selecting the suitable separation process. It is evident from Figure 10 that, there is a weight loss of about 1% due to the moisture content, which is shown as the region 'ab'. Above 2000^{C}., there is a weight loss of about 2% due to goethite in the region' bc' as this mineral reduces to hematite at this zone. Above this temperature (in the area'CD'), kaolinite decomposes to meta-kaolinite and MnO_2 converts to Mn_2O_3. It is also seen that above 7000^{C}., the weight loss is about 2% which may be due to the conversion of Mn_2O_3 to Mn_3O4. The total weight loss is about 10%, which resembles the LOI value of the sample.

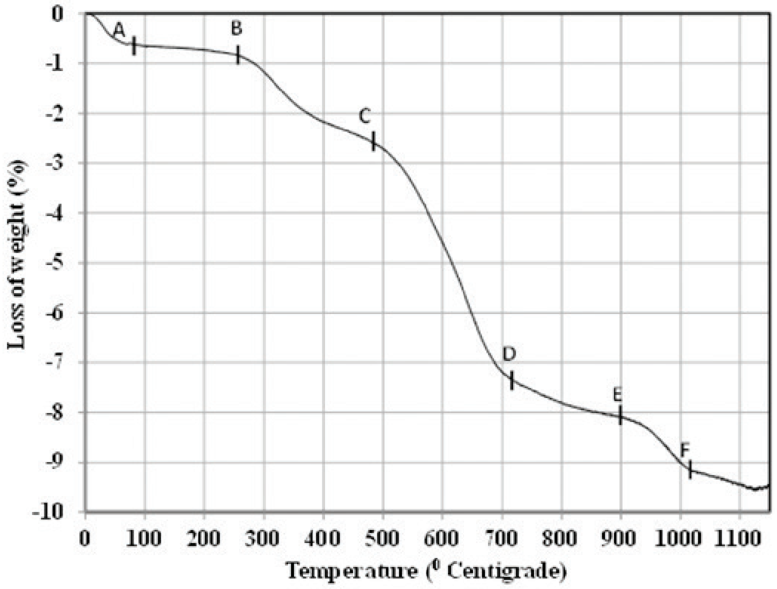


Figure 10 : Weight loss graph for the low-grade manganese fines.

3.10. Bond work index

The work index of the manganese ore at 150µmis given in Table 8. It can be observed that the grindability of all these listed samples are identical to each other. The bond work index of these samples is varied between 11.4 to 12.8 kWh/t. The higher value of the Bond Work Index (BWi) is reported for sample B, and the minimum value is reported for sample C.

Table 8. Bond work index values for the manganese ores

Source Details	Bond Work index (kW/t)
Sample A	11.9
Sample C	11.4
Sample B	12.8
Sample E	12.1
Sample D	12.5
Mixed sample	12.3

3.11. Magnetic separation studiespermanent roll magnetic separator

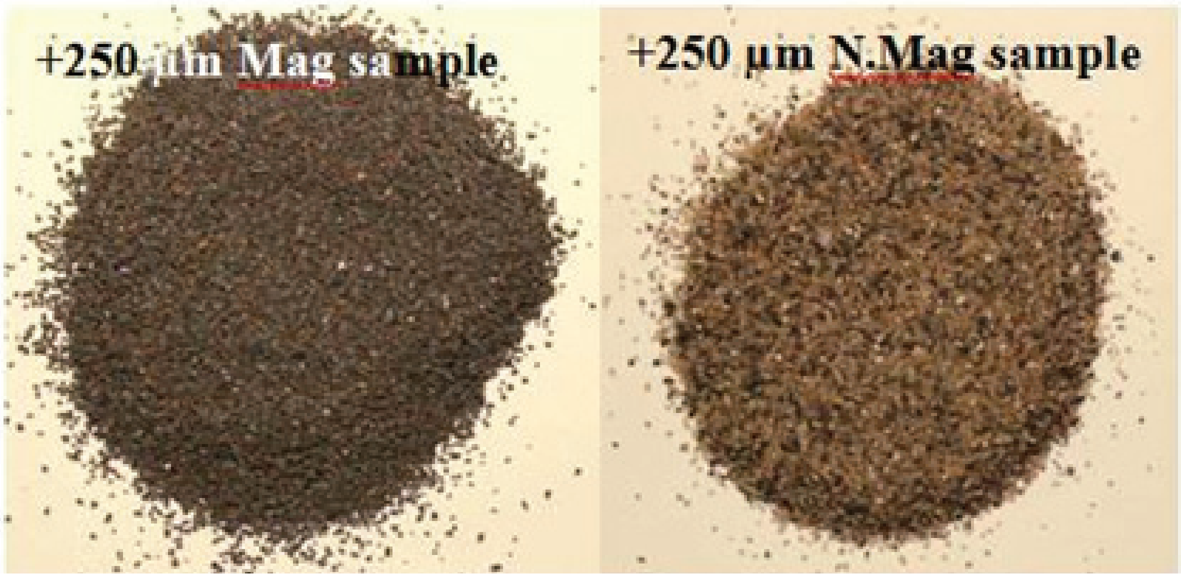
All the sieve fractions of as-received samples were subjected to dry magnetic separation studies by Permroll magnetic separation to study the response of dry magnetic separation. The studies indicated that the magnetic fraction increases with decreasing size due to better liberation in silica phases. The magnetic fraction is always high in manganese as well as iron content with low silica content. Size classification of the as-received sample and weight % of the magnetic and non-magnetic fractions (by Permroll magnetic separation) and each fraction's results were presented in Table 9. For the visual look at how the separation took place can be seen/observed from Figure 11. XRD analyzed the magnetic and non-magnetic products' detailed minerals, and their interpreted charts were presented in Figure 12 (Magnetic product) and Figure 13 (non-magnetic product). The mineralogy, by XRD, for the magnetic products are lithiophorite; pyrolusite; cryptomelane; hematite; goethite with minor amounts of quartz. The mineralogy, by XRD, for the non-magnetic products are quartz and kaolinite with minor amounts of kaolinite. It is further indicated that the silica gets liberated from the sample <75µm. In the coarser size fractions' magnetic product indicated iron is more than that of the manganese content. But at the finest size fractions, iron and manganese's content in the magnetic fractions is more or less the same indicating non-liberation of the iron phase from manganese phases.

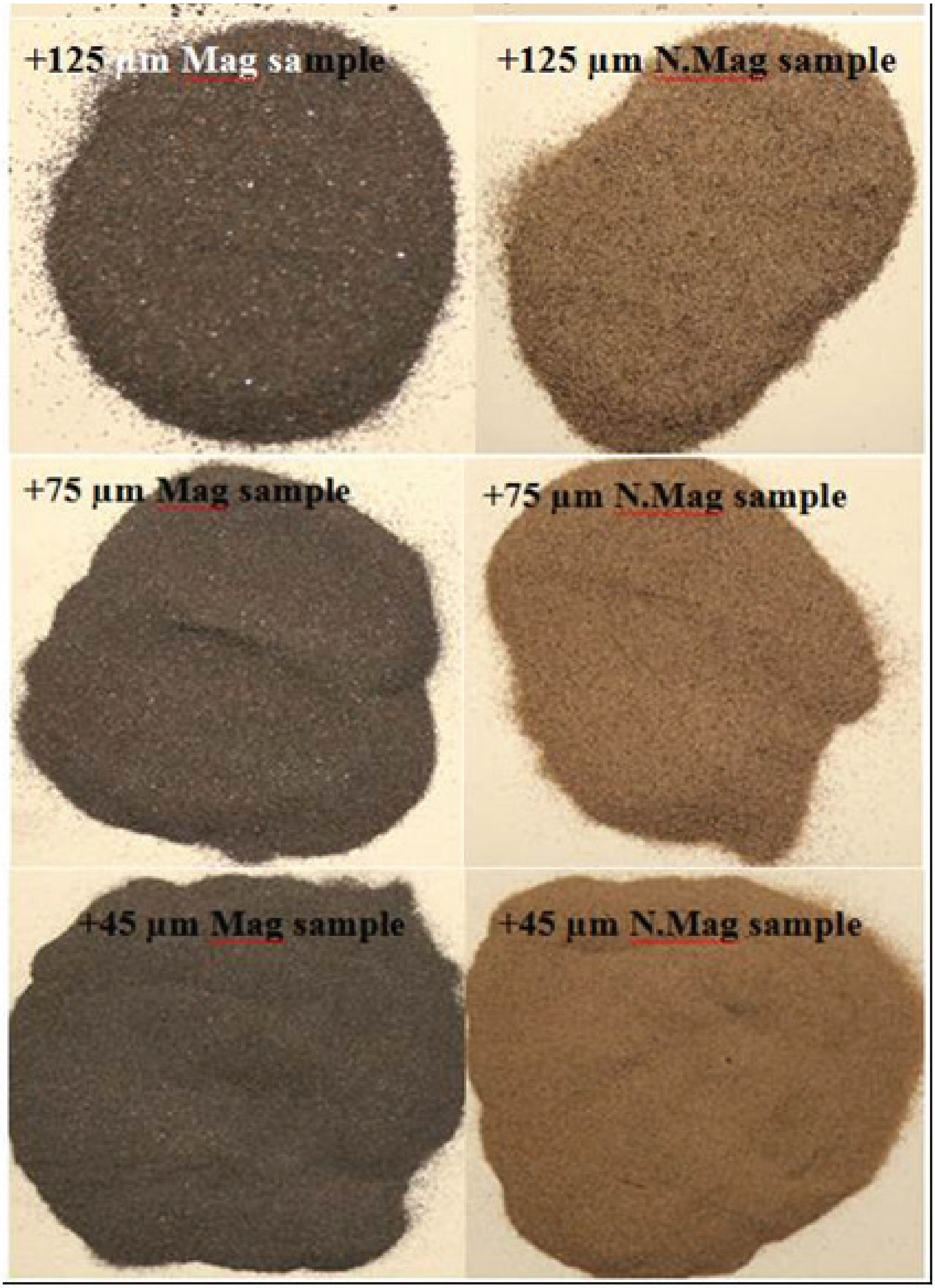
Table 9 : Results of dry magnetic separation of sized fraction of as-received sample.

Size fraction	Wt (%) w.r.t. feed	Product	Wt (%)	Assay Value (%)			
				Mn	$Fe_{(T)}$	SiO_2	Al_2O_3
-10 +6 mm	15.6	Magnetic	8.2	21.2	34.9	2.7	2.8
		Non-magnetic	91.8	33.4	25.6	1.6	3.5
		Feed		32.4	26.4	1.7	3.4
-6 +3 mm	14.9	Magnetic	24.0	25.0	33.1	2.6	2.5
		Non-magnetic	76.0	31.2	24.0	6.4	4.3
		Feed		29.7	26.2	5.5	3.9
-3 +2 mm	16.4	Magnetic	64.3	30.6	24.3	2.9	2.9
		Non-magnetic	32.7	41.3	25.6	2.5	5.5
		Feed		33.2	24.0	2.7	3.7

-2 +1 mm	6.5	Magnetic	89.2	29.9	25.2	3.2	3.6
		Non-magnetic	10.8	44.9	23.2	30.7	6.2
		Feed		31.5	25.0	6.2	3.9
-1 +0.5 mm	12.1	Magnetic	90.9	30.5	25.8	3.6	3.9
		Non-magnetic	9.2	41.3	30.0	47.9	5.4
		Feed		31.5	26.2	7.7	4.0
-0.5 +0.25 mm	6.5	Magnetic	85.9	28.3	25.4	3.5	4.0
		Non-magnetic	14.1	17.6	33.8	67.4	5.0
		Feed		26.8	26.6	12.5	4.1
-0.25 +0.125 mm	4.1	Magnetic	83.6	26.6	26.2	4.0	4.0
		Non-magnetic	16.4	11.2	27.1	81.8	4.3
		Feed		24.1	26.3	16.7	4.0
-0.125 +0.075 mm	2.4	Magnetic	84.0	27.2	26.2	6.6	4.1
		Non-magnetic	16.0	5.2	26.5	75.2	3.8
		Feed		23.7	26.2	17.6	4.1
-0.075 +0.045 mm	2.1	Magnetic	80.5	27.5	24.1	12.2	4.0
		Non-magnetic	19.5	5.7	31.9	41.1	2.8
		Feed		23.3	25.6	17.9	3.8
-0.045 mm	19.5	Magnetic	55.3	18.8	18.9	21.8	14.8
		Non-magnetic	44.7	16.2	25.7	19.2	11.9
		Feed		17.7	21.9	20.7	13.5

Figure 11 : Particle view of magnetic separation of sized samples.




+125 µm Mag sample
+125 µm N.Mag sample
+75 µm Mag sample
+75 µm N.Mag sample
+45 µm Mag sample
+45 µm N.Mag sample

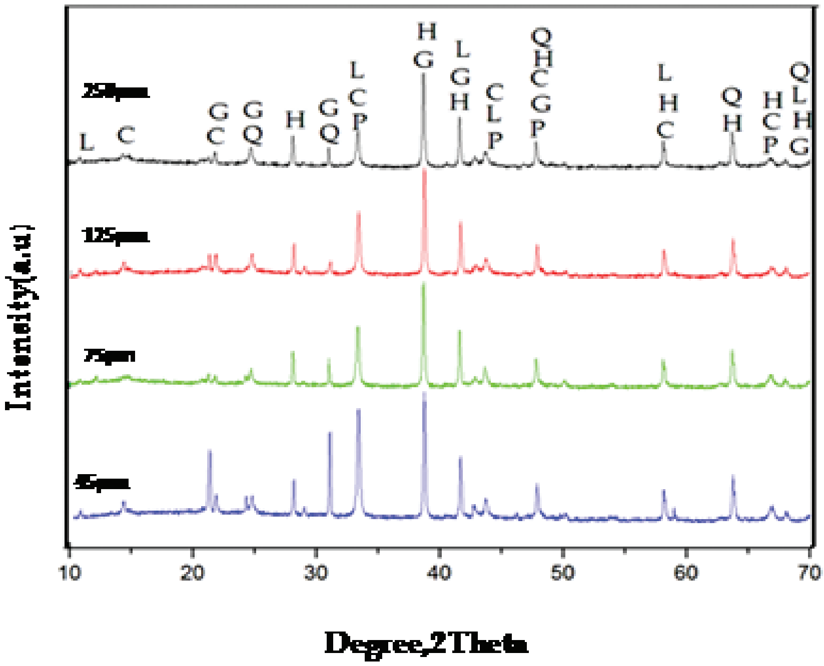


Figure 12: X-Ray diffraction pattern of the magnetic products, obtained by permroll magnetic separation, of the different size classified fractions. The different size fractions are against the individual XRD patterns (L=Lithiophorite; P=Pyrolusite; C=cryptomelane; H=Hematite; G=Goethite; Q=Quartz.).

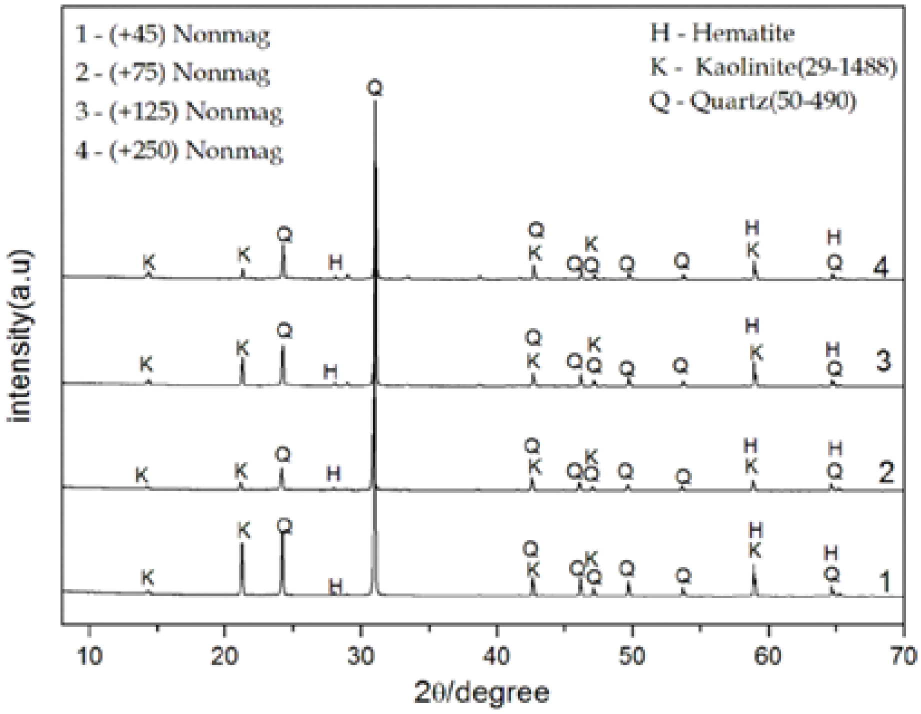


Figure 13 : X-Ray diffraction pattern of the non-magnetic products, obtained by perm roll magnetic separation, of the different size classified fractions. The different size fractions are against the individual XRD patterns.

3.12. Wet high-intensity magnetic separation results

The studies were carried out using a wet high-intensity magnetic separator (WHIMS) by varying the particle size and magnetic field intensity. Then from each test, magnetic and non-magnetic fractions were collected and weighed and subjected to an elemental analysis reported in Table 10.

From Table 10, it is observed from the data the silica and alumina values are lower in the magnetic fractions because these are non-magnetic and are reported in the non-magnetic fractions. The total manganese content is always is higher in the magnetic fractions than the non-magnetic fraction. Maximum Mn content of 33% Mn is reported in the magnetic product at the magnetic field intensity of 1.3T with a Mn: Fe ratio of 1.4. The yield to the magnetic product at this condition is 39.4%. The total iron content is higher in the magnetic fraction than the non-magnetic fraction except in -500μm size, which could be due to the locked nature of the iron phase with that of the manganese phases.

Based on the results obtained in Table 10, the second stage magnetic separation was carried out for the magnetic product of test carried out at magnetic field intensity of 1.5T for the feed size of -500μm. Experiments are carried out at lower magnetic field intensity, and the obtained results are given in Table 11. Table 11 found that a non-magnetic product of the second stage is enriched with manganese bearing minerals. A concentrate assaying 35.9% Mn with Mn: Fe ratio of 1.7 is increased by two-stage magnetic separation in wet high-intensity magnetic separation. The non-magnetic product yield is 26.5% (52.0% of the magnetic product) with an overall manganese recovery of 34.4%. Further recovery can be achievable by desliming the feed prior to this two-stage, wet, high-intensity magnetic separation.

Table 10. Wet high-intensity magnetic separation of grounded samples.

Magnetic Field (T)	Product	Wt (%)	Assay Value (%)				Mn: Fe Ratio
			Mn	$Fe^{(T)}$	SiO_2	Al_2O_3	
Feed Particle Size (-500μm)							
0.78	Mag	7.7	27.1	30.1	4.2	3.7	0.9
	Non-mag	92.3	27.8	25.8	11.1	5.8	1.1
1	Mag	22.7	30.4	30.6	3.3	3.6	1.0
	Non-mag	77.3	26.9	24.8	12.7	6.2	1.1
1.3	Mag	39.4	33.0	23.6	3.1	3.3	1.4
	Non-mag	60.6	24.3	27.7	15.5	7.1	0.9
1.5	Mag	51.0	33.4	24.8	2.5	3.3	1.3
	Non-mag	49.0	21.8	27.5	19.0	8.0	0.8
Feed Particle Size (-210μm)							
0.78	Mag	21.8	29.3	28.8	4.2	3.5	1.0
	Non-mag	78.2	27.3	25.4	12.4	6.2	1.1
1	Mag	36.0	31.7	26.9	3.2	3.3	1.2
	Non-mag	64.0	25.5	25.6	14.8	6.9	1.0
1.3	Mag	43.8	32.6	28.3	3.3	3.6	1.2
	Non-mag	56.3	23.9	24.4	16.3	7.2	1.0

1.5	Mag	36.9	31.5	23.9	4.2	4.0	1.3
	Non-mag	63.1	25.5	27.4	14.3	6.6	0.9
Feed Particle Size (-125µm)							
0.78	Mag	22.5	29.9	31.6	2.1	3.3	0.9
	Non-mag	77.5	27.1	24.5	13.1	6.3	1.1
1	Mag	35.7	31.4	27.3	3.5	3.5	1.2
	Non-mag	64.3	25.6	25.4	14.5	6.8	1.0
1.3	Mag	40.7	32.1	28.2	3.6	3.8	1.1
	Non-mag	59.3	24.7	24.7	15.4	6.8	1.0
1.5	Mag	45.7	32.3	25.9	3.7	3.7	1.2
	Non-mag	54.3	23.8	26.3	16.4	7.2	0.9
Feed Particle Size (-75µm)							
0.78	Mag	22.3	29.3	32.5	2.0	3.2	0.9
	Non-mag	77.7	27.2	24.3	13.1	6.3	1.1
1	Mag	30.8	30.9	27.0	3.4	3.4	1.1
	Non-mag	69.2	26.3	25.7	13.8	6.6	1.0
1.3	Mag	38.1	32.2	28.8	3.1	3.5	1.1
	Non-mag	61.9	25.0	24.5	15.2	6.9	1.0
1.5	Mag	41.4	31.0	30.4	3.2	3.5	1.0
	Non-mag	58.6	25.4	23.1	15.8	7.1	1.1

Table 11. Results of the second stage wet high-intensity magnetic separation

Magnetic Field (T)	Product	Wt (%)	Assay Value (%)				Mn: Fe Ratio
			Mn	$Fe^{(T)}$	SiO_2	Al_2O_3	
0.78	Mag	28.0	29.3	29.0	3.2	2.7	1.0
	Non-mag	72.0	35.0	23.2	2.2	3.6	1.5
1	Mag	38.0	31.4	29.3	3.3	2.8	1.1
	Non-mag	62.0	34.6	22.0	2.0	3.6	1.6
1.3	Mag	48.0	30.7	28.6	3.1	5.8	1.1
	Non-mag	52.0	35.9	21.3	2.0	1.0	1.7

4. Summary and Conclusions

Low-grade manganese fines from the Joda region, India, beingsubjected for a detailed integrated instrumental characterization through physical, chemical and mineralogical aspects. Based on these characterization findings, few probe tests on the feasibility of separation through gravity and magnetic separation were studied and below listed points are summarized.

- The particle size of the as-received low-grade manganese ore fines from the Joda region was below 10 mm and 60% of the total mass with particle size coarser than 0.5 mm.
- Elemental analysis of these fines indicated that the collected fines varied from 24% Mn to 31% Mn with anaverage value of 27.7% Mn in the mixed sample. Similarly,the Mn: Fe ratio of

these fines were varied from 0.79 to 1.93 with an average Mn:Fe ratio value of 1.06 for the mixed sample.

- The magnetic susceptibility value of these low-grade manganese fines varied between 0.63 to 1.13 X 10-3 m3/kg and this value of 0.79 X 10-3 m3/kg was measured for the mixed sample.
- Mineralogical analysis of low-grade manganese fines indicated pyrolusite, cryptomelane and lithiophorite as the manganese bearing minerals whereas hematite, goethite, quartz and kaolinite are the gangue mineral phases.
- The automated mineral analysis is concluded that the mixed sample contains 38.78% of manganese bearing minerals (pyrolusite,cryptomelane, lithiophorite and Mn-silicates) and 39.71% iron-bearing minerals (hematite, goethite and limonite).
- Feasibility studies for the separation of manganese-bearing minerals using gravity concentration were visualized through heavy liquid separation and concluded that no substantial separation could be achieved using gravity separation.
- Separation in dry permanent roll magnetic separator indicated that the separation is effective at intermediate size viz. -2+0.5mm, and it is found that it is challenging to separate iron-bearing gangue mineral phases.
- A concentrate assaying 35.9%Mn with Mn: Fe ratio of 1.7 is enriched by two-stage magnetic separation in wet high-intensity magnetic separation. The yield of the non-magnetic product is 26.5%, with an overall manganese recovery of 34.4%.
- Wet high-intensity magnetic separation results concluded that single-stage magnetic separation of grounded fines enriched marginally. However, two-stage magnetic separation at higher and lower magnetic field intensity yielded a better result.Further recovery in this process can be achievable by desliming the feed prior to this two-stage wet high-intensity magnetic separation.
- Effective separation of manganese-bearing minerals and iron phases can be tried using high-temperature reduction roasting.

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ARTIFICIAL INTELLIGENCE IN THE MINING INDUSTRY

Deepak Vidyarthi[1]

ABSTRACT

By 2047, marking India's centenary of independence, the nation's transition from Amrut Kaal to Shatabdi Kaal is set to be driven by transformative advancements in Artificial Intelligence (AI) and Virtual Reality (VR). These technologies are playing pivotal roles in enhancing mine safety and optimizing production through innovative solutions. India's recent participation in the US-led Minerals Security Partnership (MSP) and the $2 million grant initiative for commercializing AI applications further underscores the nation's commitment to integrating cutting-edge technology into the mineral industry.

Emerging technologies such as Artificial Intelligence (AI), Machine Learning (ML), Augmented Reality (AR), Blockchain, Drones, Internet of Things (IoT), Robotics, 3D Printing, Virtual Reality (VR), Autonomous Vehicles, Ore Sorting, and Predictive Maintenance are reshaping key aspects of the mineral sector. These advancements significantly impact areas like exploration, safety, risk assessment, environmental sustainability, and supply chain management. In particular, AI and ML are revolutionizing mineral exploration and mining operations, offering predictive capabilities and process optimization.

This paper explores the application of these technologies in the mineral industry, with a special focus on AI-driven innovations. To meet the objectives of the National Steel Policy, which targets 300 million tonnes (MT) of steel production and an increase in per capita steel consumption from 60 kg to 160 kg by 2030, significant emphasis is placed on sustainable and efficient resource utilization. Achieving the projected iron ore demand of 437 MTPA, up from the current 251 MTPA, requires a streamlined and environmentally responsible approach to ore transportation and processing.

The paper highlights key technological innovations essential for addressing these challenges and underscores their transformative potential in achieving the nation's ambitious production and sustainability goals.

Key Words : Centenary, Amrut kaal, Shatabdi kaal, MSP, VR, Drones, IoT, Innovations, National Steel Policy, Consumption, Per Capita, 300 MTPA, 437 MTPA, Cost effective, environmental-friendly, AI, ML.

Introduction

India's proactive strides toward sustainable development and technological advancement were underscored during the recent visit of the Honourable Prime Minister of India to the United States. Among the significant outcomes of the visit, India joined the Minerals Security Partnership (MSP), a U.S.-led initiative aimed at ensuring a diversified and sustainable supply chain for critical energy minerals (Sharma and Kashyap, 2024). This collaboration

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highlights India's commitment to securing resources vital for its growing economy while adhering to high environmental, social, and corporate governance (ESG) standards. A $2 million grant programme was launched to foster the commercialization of Artificial Intelligence (AI) and other transformative technologies, marking another milestone in India's journey toward technological leadership.

The Minerals Security Partnership (MSP) is a multinational alliance comprising key global players, including Australia, Canada, the United States, Japan, South Korea, and the European Union, among others. The partnership focuses on securing a stable supply of critical minerals essential for clean energy technologies, reflecting a shared vision for sustainable industrial growth and climate action.

Artificial Intelligence in Mining and Beyond

Artificial Intelligence (AI), a cornerstone of modern technology, emulates human cognitive processes to execute complex tasks such as decision-making, data analysis, and language translation. From autonomous vehicles and virtual reality systems to advanced healthcare diagnostics and fraud detection in e-commerce, AI is reshaping industries. In the education sector, AI enables the creation of smart content, personalized learning experiences, and global classrooms. Its applications extend to industrial safety, navigation systems, and robotics, showcasing its versatility and transformative potential.

In the mining sector, AI and ML are poised to revolutionize operations by leveraging big data and advanced algorithms. Applications range from autonomous haulage and aerial mapping using drones in open-cast mining to dust concentration prediction and roof support monitoring in underground mining. AI facilitates automation, enhances safety, and optimizes resource management, contributing to both efficiency and sustainability. Common applications across mining operations include environmental monitoring, mineral exploration, equipment maintenance, and the development of digital twins for simulating real-world processes.

Challenges in AI Adoption for Mining

Despite its immense potential, implementing AI in mining poses significant challenges. High initial capital investments, inadequate infrastructure in traditional mining setups, and regulatory hurdles are major obstacles. The complexity of AI systems demands highly skilled professionals, creating a need for substantial workforce training and upskilling. Concerns about AI's broader impact on employment, economics, and societal dynamics further complicate its adoption. As the technology is still in its nascent stages, careful planning, expertise, and phased implementation are critical for its successful integration into the mining industry.

By addressing these challenges and fostering innovation, India is poised to harness AI's capabilities to transform its mining sector and beyond, aligning with global trends and setting benchmarks for sustainable and technologically advanced industrial practices.

EMERGING TECHNOLOGIES SHAPING THE MINERAL INDUSTRY

Emerging technologies are likely to significantly transform the mineral industry in the coming years, introducing new efficiencies, capabilities, and safety improvements. Artificial intelligence (AI) and machine learning (ML) are at the forefront of this revolution, enabling more precise predictive analytics for exploration, mineral processing, and resource management. These technologies help optimize operations by analysing vast amounts of data to uncover patterns and make better-informed decisions. The Internet of Things (IoT) also plays a crucial role, with sensors and connected devices offering real-time monitoring of equipment, environmental conditions, and processes. This allows for predictive maintenance, reducing downtime and increasing productivity. Augmented reality (AR) and virtual reality (VR) are enhancing training and remote support by providing immersive simulations and interactive experiences for workers in hazardous environments or remote locations. Drones, equipped with advanced sensors and cameras, are revolutionizing exploration and surveying by providing high-resolution aerial imagery and mapping capabilities in hard-to-reach areas. Robotics further extends automation, handling dangerous tasks and improving efficiency in mining operations. Meanwhile, blockchain technology is gaining attention for its potential in improving transparency and traceability in the supply chain. Lastly, digital twins, virtual replicas of physical assets, are helping operators model and optimize performance, enabling real-time insights into operations and predictive maintenance. These technologies collectively promise to reshape the industry, enhancing productivity, safety, and sustainability.

INTERNET OF THINGS (IOT)

The Internet of Things (IoT) refers to physical objects or groups of objects equipped with sensors, processing capabilities, software, and other technologies that enable them to connect and exchange data with other devices and systems via the Internet or other communication networks (Kopetz and Steiner, 2022).

Several industries have integrated IoT into their mining operations. One example is Hindustan Zinc's SindesarKhurd (SK) Mine in India, which adopted IoT technology in partnership with Newtrax in 2018.

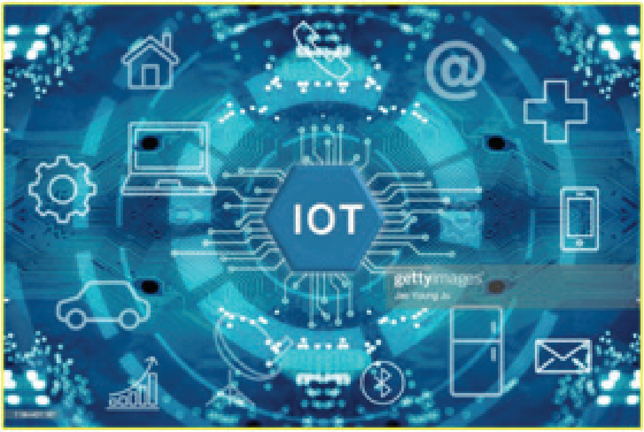

Figure1: Internetof Things (IOT)
(Source : Wireless communication network)

Applications of IOT in mining industry

The Internet of Things (IoT) is transforming the mining industry through various innovative applications. Autonomous mining equipment enhances operational efficiency and safety by reducing human involvement in hazardous tasks. Location and proximity sensors improve safety by detecting and alerting workers to potential risks. On-demand ventilation systems optimize airflow, ensuring proper ventilation while conserving energy. Equipment sensors enable predictive maintenance, minimizing downtime and reducing repair costs. Fleet management and tracking capabilities streamline operations by providing real-time data on vehicle performance and location. Visualization software empowers decision-makers with actionable insights by presenting complex data in an accessible format, driving efficiency and sustainability.

Benefits of IOTin the mining nndustry

The Internet of Things (IoT) is revolutionizing the mining industry by offering significant benefits. It saves time through real-time data collection and analysis, streamlining operations and reducing downtime. Enhanced safety standards are achieved via IoT-enabled sensors that monitor hazardous conditions and ensure worker protection. Automation advancements, such as autonomous vehicles and remote-controlled equipment, increase efficiency and minimize human intervention in high-risk areas. Predictive maintenance powered by IoT ensures equipment health by identifying issues before failures occur, reducing repair costs and delays. Additionally, IoT solutions optimize energy usage, lowering operational expenses and supporting sustainable practices, making mining more cost-effective and environmentally friendly.

MACHINE LEARNING (ML)

Machine learning, a subset of artificial intelligence (AI), relies on algorithms trained on data to create models capable of performing complex tasks (Tyagi and Chahal, 2020). Today, the majority of AI applications are powered by machine learning techniques.

This technology has numerous applications across diverse fields. For instance, it enables image and speech recognition, powers traffic prediction systems and supports self-driving car technology. Machine learning is also extensively used in training and assessment through simulators, identifying damaged car parts, predicting stock prices, and analyzing emotions. These examples highlight the versatility and transformative potential of machine learning in solving real-world problems and optimizing decision-making processes across industries.

BLOCKCHAINS

Blockchain technology serves as a decentralized, immutable ledger designed to streamline the recording of transactions and the management of assets within a business network. These assets may be tangible, such as mining, real estate, vehicles or cash, or intangible, like intellectual property or digital currencies. A blockchain operates as a distributed ledger, comprising an expanding sequence of data blocks. Each block is securely interconnected using cryptographic hashes, ensuring data integrity and resistance to tampering (Swan, 2015). Each block contains a cryptographic reference to its predecessor, forming a chain-like structure that enhances security and transparency. This structure underpins blockchain's ability to foster trust and efficiency across various industries.

Benefits of Blockchain

Enhanced trust, improved security, and increased efficiency are key pillars driving modern technological advancements. Trust is built through transparent systems and reliable processes, fostering stronger relationships between stakeholders. Security plays a crucial role, with robust measures designed to protect sensitive data and ensure the integrity of operations. Efficiency gains arise from streamlined workflows and automation, enabling organizations to optimize resource use and achieve their objectives more effectively. Together, these elements create a foundation for innovation, empowering businesses to thrive in a competitive and rapidly evolving landscape.

Figure2 : Blockchain
(Source : NASDAQ and San-Francisco blockchain company)

SUPPLY CHAIN

A supply chain is a network of individuals and companies who are involved in creating a product and delivering it to the consumer (Fathollahi-Fardet. *al, 2022).*

Links on the chain begin with the producers of the raw materials and end when the van delivers the finished product to the end user.

A supply chain, sometimes expressed as a "supply-chain", is a complex logistics system that consists of facilities that convert raw materials into finished products and distribute them to end consumers.

ROBOTICS

Robotics is a fascinating and rapidly evolving field that combines principles and techniques from various disciplines, including mechanical engineering, electrical engineering, computer science, and artificial intelligence. At its core, robotics involves the design, construction, operation, and application of robots, which are machines programmed to perform tasks either autonomously or with guidance. This interdisciplinary approach has led to the development of robots capable of performing a wide range of functions, from industrial automation to assisting in medical procedures and even exploring distant planets (Dzedzickis *et al., 2021).*

Robots are remarkably diverse, both in their design and the environments where they are deployed. Some are built for industrial purposes, such as assembling cars in factories, while others are designed for healthcare, performing tasks like assisting surgeries or helping patients with mobility issues. Robots are also employed in hazardous environments, such as deep-sea exploration, nuclear facilities, or disaster zones, where human presence might be too risky. In everyday life, service robots, such as robotic vacuum cleaners or personal assistants like robotic pets, have become increasingly common.

Despite this diversity in function and form, all robots share three foundational components in their design and construction :

1. Mechanical Construction : A robot's mechanical design is what gives it its form and functionality. This aspect includes the frame, joints, and actuators – the parts responsible for movement and interaction with the physical world. The mechanical design varies widely depending on the robot's intended purpose. For example, an industrial robot arm requires a robust, precise mechanical structure to handle repetitive tasks like welding or assembling components, while a humanoid robot might have a more complex design to mimic human movement and dexterity.
2. Electrical Components: The electrical subsystem provides the power and control needed for the robot to operate. This includes batteries, motors, sensors, and circuits. Sensors play a critical role by collecting data about the robot's surroundings, such as temperature, distance, or pressure, enabling it to interact effectively with its environment. For instance, autonomous vehicles rely on a combination of cameras, LiDAR, and radar sensors to navigate roads safely. The electrical components also include the wiring and control systems that ensure the mechanical parts perform their functions accurately and efficiently.
3. Software: Software acts as the brain of the robot, guiding its actions and decision-making processes. A robot's software determines when, how, and why certain actions are performed, making it essential for achieving autonomy and adaptability. Robots equipped with artificial intelligence (AI) can process data from their environment, recognize patterns, and make decisions without direct human input. For example, warehouse robots use AI to identify and retrieve items from shelves. Simpler robots might rely on remote control (RC) or pre-programmed instructions to perform tasks. A hybrid approach, combining both AI and RC functionalities, is also common, particularly in applications requiring human oversight alongside autonomous capabilities.

One of the most transformative aspects of modern robotics is the integration of artificial intelligence. AI enables robots to learn from their experiences, adapt to new situations, and perform tasks with increasing sophistication (Hussain et.Al, 2024). Machine learning, a subset of AI, allows robots to improve their performance over time by analysing data and recognizing patterns. For instance, robotic vacuum cleaners use AI to map the layout of a home, optimize cleaning paths, and avoid obstacles.

Moreover, robots with AI can interact with their environments in ways that were previously unimaginable. They can detect and respond to stimuli, such as recognizing human emotions through facial expressions or voice tones. Social robots, like those used in customer service or education, leverage these capabilities to engage with people more naturally. Similarly, medical robots equipped with AI can analyze patient data, assist in diagnostics, and even perform minimally invasive surgeries with exceptional precision.

Robotics in the mining industry enhances safety and efficiency (Pilyugin, 2023). Autonomous haul trucks, robotic drilling systems, and drones for site monitoring are examples. They reduce human risk, optimize operations, and improve productivity in challenging mining environments.

However, a major challenge lies in ethical considerations. As robots become more autonomous, questions about accountability and decision-making arise. For instance, if an autonomous vehicle is involved in an accident, determining responsibility can be complex. Similarly, the increasing use of robots in the workforce raises concerns about job displacement and economic inequality.

Balancing technological progress with societal impacts is a crucial aspect of responsible robotics development.

Inspite of these challenges, the future of robotics holds immense potential. Researchers and engineers are continually exploring new ways to enhance robot capabilities, making them more versatile, efficient, and intelligent. Advances in materials science are leading to the development of softer, more flexible robots that can safely interact with humans and adapt to various environments. For instance, soft robotics is being used to create robotic grippers capable of handling fragile objects.

VIRTUAL REALITY

Virtual reality (VR) is an interactive computer-generated experience taking place within a simulated environment. It incorporates mainly auditory and visual feedback, but may also allow other types of sensory feedback. This immersive environment can be similar to the real world or it can be fantastical (Mohd and Kumar 2023).

Figure3 : Virtual Reality

(Source : New South Wales Advanced Visualisation and Interaction Environment)

HOW AI AND VR ENHANCE MINE SAFETY

Artificial intelligence (AI) and virtual reality (VR) are playing a transformative role in enhancing safety within mines (Soofastaei, 2024). They enable real-time insights that help predict and prevent hazardous situations while issuing immediate alerts to mitigate risks. By leveraging AI-powered tools such as autonomous vehicles, sensors, and drones, the need for human workers to undertake perilous tasks is significantly reduced. These technologies also improve operational efficiency by predicting maintenance requirements, identifying optimal drilling sites, and streamlining ore processing. AI and sensors analyse real-time data to monitor changes in critical factors like temperature and vibrations, providing early warnings to operators and drivers to prevent potential dangers. Additionally, real-time analytics and quality data help identify process failures, reducing the likelihood of accidents and injuries. Together, AI and VR are revolutionizing mining safety by providing predictive capabilities, automating dangerous tasks, and enabling proactive decision-making (Shah and Mishra, 2024). These advancements not only enhance worker safety but also contribute to cost-effective and efficient mining operations.

AI AND AUTOMATION IN MINING

Artificial intelligence and automation are revolutionizing the mining industry by reducing reliance on human labour and incorporating partially or fully automated equipment and techniques (Firoozi, 2024). Automation combines advanced technologies such as Artificial Intelligence, the Internet of Things (IoT), and robotics to enhance mining operations. This integration offers several key advantages. Firstly, it significantly lowers overall costs while ensuring safety remains a priority. Secondly, it improves consistency and continuity in mining processes. Thirdly, automation boosts overall productivity by enhancing equipment performance, leading to better fuel efficiency, reduced unscheduled maintenance, and smoother operations. These advancements not only optimize resource use but also promote more efficient, safer, and cost-effective mining practices.

AUTONOMOUSH AULAGE

Autonomous haulage has emerged as a transformative solution for transporting materials in open-pit mines, where limited haulage passages pose challenges for traditional truck operations (Owens, 2021). By leveraging automated vehicles and advanced AI algorithms for routing, significant improvements can be achieved, including faster hauling, greater fuel efficiency, reduced spot creation and wait times for each truck, minimized exception handling, and a potential 15% reduction in production costs. These advancements not only optimize operational efficiency but also enhance safety and sustainability in mining processes. Leading manufacturers worldwide are now producing driverless trucks, trains, and excavators, showcasing the rapid adoption of autonomous technologies in the mining industry.

Figure 4 : Autonomous Truck

(Source : Autonomous Truck-793F)

AUTONOMOUS VEHICLES

Self-driving vehicles are vehicles that use sensors and artificial intelligence to transport people on roads autonomously without human input (Hamza et al., 2023). Self-driving cars are also known as autonomous vehicles or driverless cars.

How Do Self-Driving Vehicles Work?

The main goal of self-driving vehicles is to drive from one point to another point safely. For this purpose, they operate on a pre-established map. This map is called a high-definition map or HD Map. Self-driving vehicles use a combination of radar, video cameras, LiDAR and GPS to locate themselves and surrounding vehicles within their HD Map.

TRUCK DISPATCH SYSTEM

In truck-shovel open cast mining, truck haulage is typically the most expensive unit operation. Implementing a dispatching system can improve operational efficiency by reducing waiting times and providing additional benefits (Reddy, 2013). These include minimizing shovel wait time (MSWT), optimizing the use of Heavy Earth Moving Machinery (HEMMs), and reducing machinery idle time. Objectives of a Truck Dispatch System (TDS) also encompass health monitoring of HEMMs, ensuring quality control, managing crusher throughput, and enabling online breakdown reporting. Furthermore, it enhances mine safety, supports extensive real-time reporting, and provides an electronic overview of mine activities. Efficient material transportation, which accounts for approximately 50% of operating costs in an open pit mine, is another key area of focus. Dynamic dispatching, enabled by GPS technology, automates the allocation of trucks to shovels, optimizing truck cycle time (MTCT), reducing truck waiting time (MTWT), and preventing shovel saturation (MSS), ultimately meeting production and quality targets.

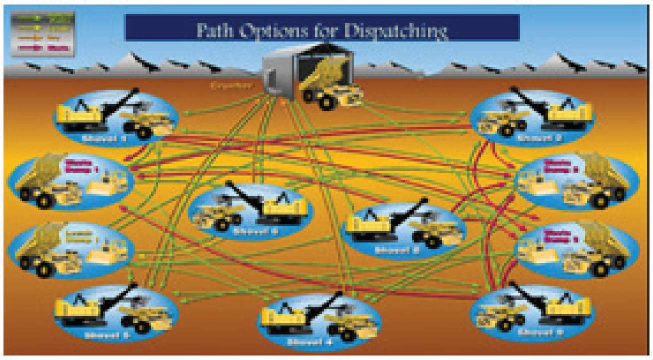

Figure 5 : Truck Dispatch System

(Source : Introduction of Al Despatch)

AUTOMATED DRILLS AND INTELLIGENT DRILLING SYSTEMS

Automated drills and intelligent drilling systems play a vital role in modern mining operations (Li et. al, 2022) particularly in drilling and blasting, which are essential for every mining project. Drilling is conducted based on a predetermined pattern tailored to the blasting objective, rock type, formation, and drilling location. The typical drilling cycle includes steps such as drill positioning, levelling with jacks, drilling holes, cleaning, and repeating the process. In automated systems, the drill independently moves between holes, guided by pre-established GPS coordinates.

For underground mining, longwall mining stands out as a widely used method. It employs shearers to cut minable coal from underground seams. A typical shearer is equipped with electric motors, hydraulic systems, and a conveyor to facilitate efficient operation. Modern automated shearers rely on memory-cutting software, enabling precise cutting of the coal face. These advancements enhance efficiency, reduce manual labour, and optimize productivity in mining operations.

DIGITAL TWINS

A digital twin is a virtual representation of a physical entity—be it devices, people, processes, or systems. This technology enables cost-effective simulations of scenarios that would otherwise be expensive or impractical to replicate (Singh, et. Al, 2021). By leveraging real-time data, digital twins mirror real-world assets in a digital space, allowing data scientists and IT professionals to analyze and optimize performance. IoT sensors, log files, and other data sources are integral to collecting accurate information, which is then combined with AI-driven analytics to create precise virtual models.

Digital twins can be categorized into three primary types :

1. **Product Twins :** These models replicate physical objects to simulate scenarios, anticipate issues, and enhance product quality.
2. **Process Twins :** Often called digital twins of organizations (DTOs), these focus on optimizing workflows and designing efficient processes.
3. **System Twins :** These virtual replicas gather system-generated data to monitor, manage, and optimize entire systems.

In mining, digital twins enhance productivity by simulating work environments. They aid in planning schedules and accurately estimating operations like drilling, crushing, and extraction. Additionally, digital twins and digital threads—comprehensive records tracking a product's lifecycle—form the foundation for digital transformation, offering immense potential for improving workflows, revenue models, and stakeholder relationships.

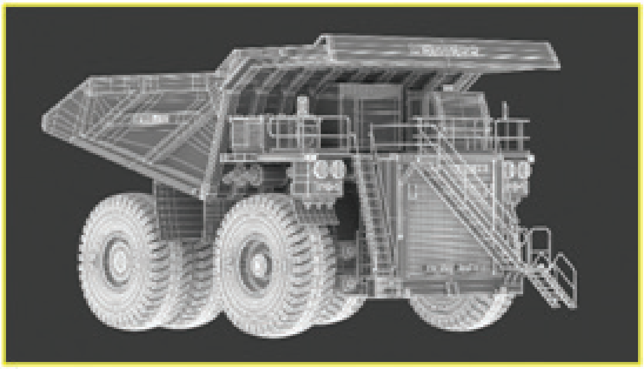

Figure 6 : Digital Dump Truck

(Source : -Belaz 75710)

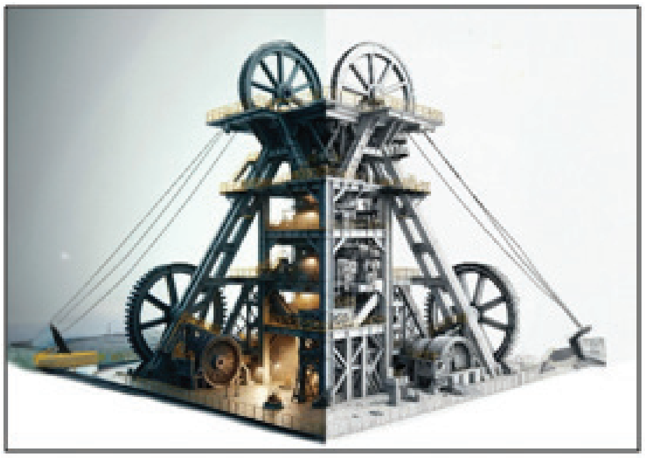

Figure7 : Digital Twin – Headgear

(Source : mining head gear)

SAFETY AND ACCIDENTANALYSIS

Accidents and safety in mining are critical concerns due to its inherently hazardous nature. Traditionally, monitoring environmental and operational parameters has been vital for understanding and preventing accidents. However, integrating AI enhances this process by enabling more precise and reliable predictions of potential accidents and safety-related factors, improving overall risk management and workplace safety (Usama *et. al, 2024).*

HEALTH MONITORING

Health monitoring in mining can be enhanced by equipping workers with wearable health tracking devices. This approach focuses on monitoring individual health rather than the entire area (Adjiski *et. Al, 2019).* Modern smartphones, equipped with advanced sensors like high-resolution CMOS image sensors, GPS, gyroscopes, accelerometers, magnetometers, ambient light sensors, and microphones, can measure various health parameters such as heart rate, heart rate variability, respiratory rate, and other conditions. By leveraging machine learning and artificial neural network (ANN) techniques, these devices can effectively analyze health data, offering a proactive solution to monitor and maintain the well-being of miners.

SMART PPES (PERSONAL PROTECTIVE EQUIPMENT)

Mine workers adhere to strict work/rest schedules to ensure safety in the challenging and hazardous mining environment. Smart personal protective equipment (PPE) enhances safety by continuously monitoring biometric data, keeping supervisors and workers informed about each individual's physical state (Podgórski,2020). This technology helps identify when a worker needs rest, reducing the risk of overexertion and fatigue-related accidents. For instance, a sudden fall might be detected through abnormal spikes in heart rate, prompting immediate assistance. Additionally, some smart PPE devices are equipped to detect toxic gases or hazardous substances, providing early warnings to prevent potentially life-threatening incidents.

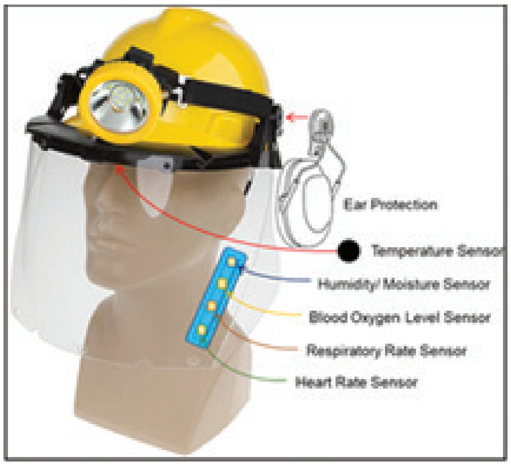

Figure 8 : Smart PPEs

(Source : Transactions of the Indian National Academy of Engineering)

IoT safety helmets are equipped with sensors that detect changes in temperature, humidity, and air quality, ensuring enhanced monitoring and safety in mining environments.

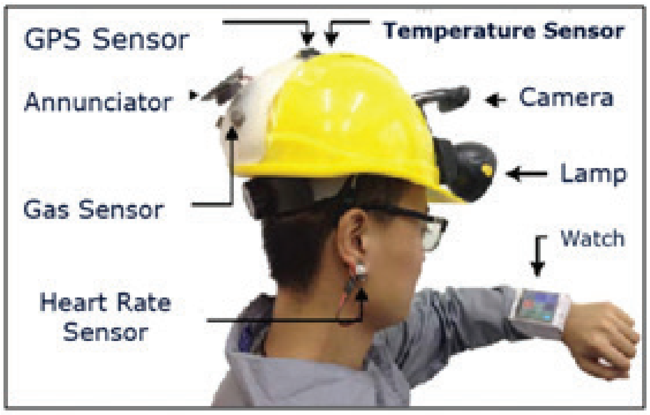

Figure 9 : IoT Safety Helmets

(source : Transactions of the Indian National Academy of Engineering)

ROCKBURST PREDICTION

Rockburst prediction is critical for high-stress mines, where the spontaneous and violent failure of rock structures poses severe risks to safety and operations. Long-term prediction methods are employed during the project design phase to evaluate site-specific risks and guide operational planning. Advanced machine learning and deep learning models, including artificial neural networks (ANN), distance discriminant analysis (DDA), support vector machines (SVM), and Bayes discriminant analysis (BDA), are commonly used due to their high accuracy (Pu *et. Al, 2019).*

These models rely on input data such as strain energy density, rock brittleness, tangential stress, failure duration time, energy storage density, and energy-based burst potential in the rock mass.

During the operational life of a mine, short-term prediction methods are deployed to detect immediate rockburst risks. Microseismic signals play a critical role in identifying potential incidents. Effective field monitoring focuses on extracting genuine microseismic signals while distinguishing seismic events from quarry blasts and other movements to ensure accurate risk assessment and mitigation.

MONITORING OF TAILINGS DAMS

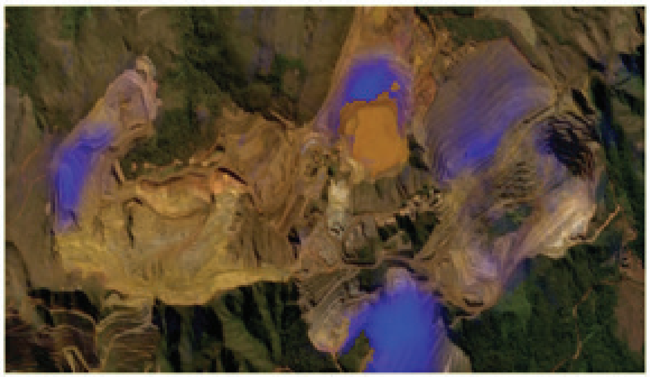

Figure 10 : Digital Tailings Dam Model
(Source : Mining Magazine)

Monitoring Of Tailing Dams Safety

Mining operations often generate more tailings than valuable minerals, producing billions of tonnes of waste annually. This slurry is typically stored in tailings dams, some of the world's largest engineered structures. However, recent catastrophic failures—such as the Brumadinho Dam in Brazil in 2019 (Thompson et. al, 2020), Williamson Gold Mine in Tanzania (2022), Lone Khin Jade Mine in Myanmar (2024), and Cadia Mine in Australia (2018)—underscore the need for enhanced safety measures (Mwanza, 2024). Advanced AI algorithms, using real-time data analysis and machine learning, detect and predict potential issues by analyzing sensor data. RTK-enabled drones offer precise measurements of dam structures, complemented by IoT devices like piezometers and inclinometers, ensuring proactive monitoring.

CONCLUSION

While digital transformation focuses on making mines smarter, new technologies and tools on the hardware, transportation, and equipment side bring unprecedented brains and brawn to all major operations.

Mining sees a huge future in Electric and Autonomous vehicles and equipment which will continue to impact the mining industry. Artificial Intelligence will be the future of Mine-Operations & Operational Safety.

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DECARBONIZING THE MINING INDUSTRY : STRATEGIES AND INNOVATIONS FOR SUSTAINABLE PRACTICES

Tuli Bakshi[1]

ABSTRACT

The mining industry stands at a pivotal moment, grappling with the dual challenges of fostering economic growth and ensuring environmental sustainability. In response to the 2015 Paris Climate Accord, and the urgent call from the Intergovernmental Panel on Climate Change (IPCC) for carbon neutrality by 2050, mining companies are increasingly committing to net-zero emissions and strengthening their Environmental, Social, and Governance (ESG) strategies. Given its energy-intensive nature and significant carbon footprint, the industry is adopting diverse measures to reduce greenhouse gas emissions. These include integrating renewable energy, enhancing energy efficiency, and leveraging advanced technologies such as digital transformation and automation.

This paper explores the industry's shift towards sustainable practices, emphasizing innovations like equipment electrification, process optimization, and biomining. Additionally, it discusses the critical role of addressing Scope 3 emissions, which encompass the entire value chain. Through detailed case studies, the paper highlights actionable strategies for achieving substantial emission reductions and underscores the importance of long-term, science-based targets for sustainable growth. Ultimately, it advocates for a comprehensive approach to decarbonization, demonstrating the potential for transformative environmental and economic outcomes in the mining sector.

1. Introduction

The race towards decarbonization accelerated significantly with the signing of the Paris Climate Accord in 2015, where 195 countries agreed to strive towards limiting global warming to 1.5 degrees Celsius above pre-industrial levels. By 2018, the Intergovernmental Panel on Climate Change (IPCC) highlighted the need for global emissions to become carbon neutral or "net zero" by 2050 to meet this goal (IPCC, 2018). This ambitious target has led companies worldwide to commit to net-zero goals and publish their environmental, social, and governance (ESG) plans to map out how they will reduce their greenhouse gas (GHG) emissions and achieve net-zero status. Achieving "carbon neutrality" means offsetting the carbon dioxide released by the company's operations, while "net zero" refers to reducing all GHG emissions across the entire supply chain.

Many mining companies are actively pursuing GHG emission reductions and planning for the long-term decarbonization of their operations. In early 2020, the International Council on Mining and Metals (ICMM) released enhanced mining principles that require members to continually improve in areas such as water stewardship, energy use, and climate change. This includes 27 of the world's largest mining companies. For the first time in history, climate

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change and related environmental issues occupied all five top spots in the World Economic Forum's 2020 global risks report (WEF, 2020). Ernst & Young's 2020 report on the top business risks facing mining and metals placed "License to Operate" at the top, and "Reducing Carbon Footprint" in fourth place (Mitchell, 2020).

Mining is an energy-intensive industry with a substantial carbon footprint, and a significant percentage of a mine's operating costs are energy-related. Modern energy strategies for miners now include not only finding the lowest-cost energy sources but also those that support carbon reduction goals. Miners face various pressures, including financial, shareholder, technological, political, regulatory, legal, and social forces, all pushing for decarbonization.

Initially, various mining organizations issued voluntary reporting guidelines. However, a universal framework was needed to ensure accuracy and consistency in emission reporting across the sector. By 2020, these organizations had agreed to work together under the Global Reporting Initiative (GRI) (Stutt, 2023; Bundock & Grizzi, 2022). The GRI Standards are now the most widely used and accepted sustainability reporting standards in the mining industry (Coles, Connors & Shaw, 2023). The GRI recently introduced a draft with 25 ESG reporting standards, inviting public comments until April 30, 2023, with the goal of publication by December 2023. The GRI standards classify GHG emissions into three categories: Scope 1 (direct emissions from owned or controlled sources), Scope 2 (indirect emissions from the generation of purchased electricity), and Scope 3 (all other indirect emissions that occur in a company's value chain) (G.R.I., 2023).

The ICMM, which represents a significant portion of the global mining industry, has also established sustainable mining principles that urge members to report their ESG performance based on GRI Standards, including Scope 1, Scope 2, and Scope 3 emissions annually. Furthermore, in March 2022, the US Securities and Exchange Commission (SEC) announced plans to standardize climate-related ESG disclosures for investors. The SEC's proposed rules would require publicly listed companies to disclose risks likely to materially impact their business and to report their Scope 1, Scope 2, and Scope 3 emissions (Warren, 2023).

The mining industry in India is crucial for the country's economic development, supplying essential raw materials for various industries. However, it is also a significant contributor to GHG emissions, making decarbonization imperative. Strategies and technologies needed to reduce carbon emissions in India's mining sector include enhancing energy efficiency, integrating renewable energy, and adopting sustainable mining practices.

2. Current State of the Indian Mining Industry

India's mining industry is a global giant, extracting a diverse range of minerals including coal, iron ore, bauxite, and limestone. While coal provides a significant portion of the country's energy needs, it also carries a heavy environmental burden. Fossil fuel dependence for operations and the inherent energy intensity of mining processes exacerbate the industry's ecological impact.

A recent report by the International Energy Agency (IEA) on methane emissions from coal mines placed India as the third-largest emitter globally in 2023, responsible for a staggering 2.8 million tonnes of methane (IEA, 2023). This figure is more than three times higher than the official data submitted to the United Nations Framework Convention on Climate Change (UNFCCC) in 2019 (0.8 million tonnes), highlighting the need for improved measurement methods (IEA, 2024). The report emphasizes that significant reductions in these emissions are achievable through cost-effective measures, potentially slashing emissions by 0.9 million tonnes and avoiding an equivalent of 80 million tonnes of CO_2 emissions (IEA, 2024).

Traditionally, ferrous and non-ferrous metals have played a critical role in India's economic growth across manufacturing, services, and agriculture. Sectors like construction, infrastructure, railways, automobiles, and process plants are major consumers of these metals. As Figure 1. illustrates, the mining industry's growth is closely linked to overall economic expansion. Iron and steel, aluminium, and coal value chains are major contributors to emissions in India due to their high production volumes and associated emission intensities. These value chains warrant primary focus when considering the industry's environmental, social, and governance (ESG) imperatives.

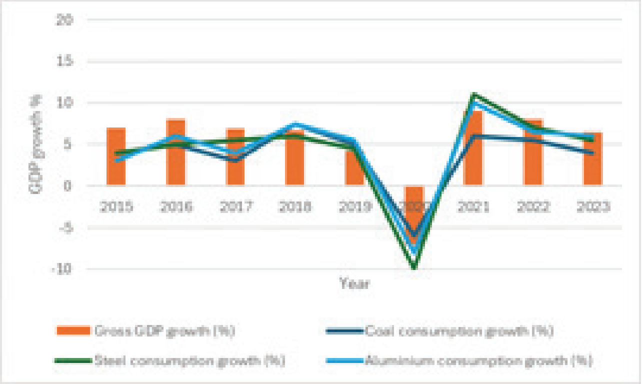

Figure 1 : India's GDP growth vs. coal, steel, and aluminium consumption growth.

Figure 1compares India's gross GDP growth with the growth rates of coal, steel, and aluminium consumption from 2015 to 2023. The bar chart represents GDP growth, while the line graphs represent the consumption growth rates of coal, steel, and aluminium. (recreated from KPMG., 2024)

The global shift towards electric vehicles is driving a surge in demand for metals like copper, nickel, lithium, manganese, cobalt, and graphite. As India embraces clean energy solutions, the requirement for minerals used in their production will also rise. The country is poised for significant expansion in capacity across all major metals and minerals, aligning with the rising demand from sectors like infrastructure, automotive, and consumer durables. Notably, zinc is expected to outpace global demand growth (2% CAGR) with a projected growth rate of 3-5%, while 20% of global copper demand growth is anticipated to originate from India and Southeast Asia between 2023 and 2028. Major metals and minerals like iron, steel, aluminium, and coal are all set for rapid growth. India's automobile and construction sectors are poised for expansion in the coming years, further propelling the demand for steel. Additionally, with the expected growth of the automotive, construction, and machinery industries, coupled with increasing applications in electrical and consumer goods sectors, India's aluminium capacity is projected to reach 12 million tonnes by 2030.

Coal is likely to remain a significant source of energy in India for the next 10-15 years, until renewable energy capacity additions reach a sufficient level to meet electricity demands. Policy initiatives like commercial mining in captive blocks and the auctioning of an increasing number of coal blocks are expected to drive coal production to 1.6 billion tonnes by 2030. India's mining industry faces the challenge of balancing its vital role in economic development with the growing need for environmental sustainability. Embracing cleaner technologies, stricter emission measurement protocols, and a strategic shift towards renewable energy sources will be crucial for the industry's long-term viability.

Table 1 : Projected Growth Rates for Major Metals and Minerals in India (Recreated from KPMG., 2024)

Metal/ Mineral	**Projected Growth Rate in India**	**Time Period**
Zinc	3-5%	2023-2028
Copper	20% of global growth	2023-2028
Aluminum	Reach 12 million tonnes	By 2030
Coal	Reach 1.6 billion tonnes	By 2030

3. Net Zero Approach

Setting achievable goals is commendable, but the pressing climate crisis necessitates more daring targets. This is where science-based targets play a crucial role. The Science Based Targets initiative (SBTi), a collaborative effort of CDP, the World Resources Institute (WRI), the World Wide Fund for Nature (WWF), and the United Nations Global Compact (UNGC), urges businesses to establish ambitious emissions reduction goals grounded in scientific research. These targets aim to help companies prepare for sustainable growth in a low-carbon future. Targets are deemed "science-based" if they align with the decarbonization levels required to limit global temperature rise to below 2 degrees Celsius above pre-industrial levels, as outlined in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) (WRI., 2023).

SBTi certainly hopes that science-based target setting will become standard business practice, and there is evidence to suggest this is already happening. In fact, in just the few years since the initiative began, over 120 companies have set SBTi-approved emissions reduction targets in line with climate science and the goals of the Paris Agreement, and an additional 320 companies are committed to following suit (SBTi., 2018). Furthermore, science-based target setting is already becoming part of the annual reporting practice of companies and the data infrastructure of institutional investors through incorporation into the CDP questionnaire and scoring. SBTi assures those companies still exploring the idea of setting a science-based target of the benefits, including increased innovation, reduced regulatory uncertainty, strengthened investor confidence and credibility, and improved profitability and competitiveness. There are also reputational benefits for companies with approved science-based targets— particularly for consumer-facing brands farther down the value chain that are facing increasing pressure from society to do their “fair share” in the fight against climate change. However, it’s worth noting that, to date, no mining company has an SBTi-approved target (Thomas & Lund., 2018). This is likely due, at least in part, to the fact that mining companies interested in setting a science-based target have two hurdles they need to overcome. The first challenge for mining companies considering setting a science-based target involves their scope 3 (value chain) emissions. In order for a science-based target to be approved, a scope 3 target is required if a company’s scope 3 emissions are at least 40% of total scope 1, 2, and 3 emissions (Thomas & Lund., 2018). If so, the scope 3 target must include the majority (at least two-thirds) of the company’s value-chain emissions (SBTi., 2018).

A recent report by CDP highlights that the mining industry faces substantial potential exposure to carbon emissions regulation within its value chain. It is estimated that scope 3 emissions from downstream customers can be, on average, 10 times, and up to 30 times higher than the operational emissions (Soliman, Fletcher, & Crocker, 2017). "The SBTi aims to make science-based target setting a standard practice for businesses, and there are promising signs that this is already underway. Since the initiative’s inception, over 120 companies have established SBTi-approved emissions reduction targets aligned with climate science and the Paris Agreement goals, with another 320 companies committed to doing the same (SBTi, 2018). Moreover, the practice of setting science-based targets is becoming integrated into annual reporting and the data infrastructure of institutional investors, particularly through the CDP questionnaire and scoring system. SBTi highlights several benefits for companies considering setting these targets, including fostering innovation, re-ducing regulatory uncertainties, boosting investor confidence and credibility, and enhancing profitability and competitiveness. Companies that secure approval for their science-based targets also gain reputational advantages, especially consumer-facing brands that face societal pressure to contribute significantly to the fight against climate change.

Despite the urgency of addressing climate change, no mining company has yet achieved SBTi approval for their emissions targets (Thomas & Lund, 2018). This is likely due to several significant challenges. One major hurdle is dealing with scope 3 emissions, which cover the entire value chain. Companies must set a scope 3 target if these emissions account for at least 40% of their total scope 1, 2, and 3 emissions (Thomas & Lund, 2018). In such cases, the scope 3 target must address the majority (at least two-thirds) of the company’s value chain emissions (SBTi, 2018)."

Currently, there is no specific decarbonization pathway for the mining sector within the Sectoral

Decarbonization Approach (SDA). Instead, mining activities like "manufacturing of nonferrous metals" fall under the "other industry" category, which includes various industries that don't fit into the six primary sectors. According to the SDA, mining companies within this category are expected to reduce their emissions intensity by approximately 87% by 2050 (SBTi, 2018). For context, from 2014 to 2016, the top mines under ICMM managed to reduce their total emissions by 15%, mainly driven by a few large companies. On average, individual companies achieved a mere 4% reduction. The 87% reduction target does not consider the diverse nature of the mining sector, treating companies with different resources (e.g., copper, lead, gold) and processes (e.g., comminution, electrowinning) uniformly. This uniform approach applies the same absolute emissions reduction percentage to all companies within the sector, aiming to keep the sector within its 2°C carbon budget if all targets are met (Thomas & Lund, 2018).

Table 2 : Emission Reduction Achievements and Targets

Metric	**Value**
ICMM Top Mines Emissions Reduction (2014-2016)	15%
Average Individual Company Reduction (2014-2016)	4%
SDA Target Reduction by 2050	87%

Meeting this target is quite challenging. Although the SDA suggests that significant reductions can be achieved through "generic efficiency improvements," such steep declines would likely have been observed already if they were straightforward to implement. The SDA does mention potential reductions in scope 2 emissions through more efficient motor systems and decarbonizing electricity, but it doesn't fully address the substantial technological advancements needed across the entire mining value chain (e.g., smelting, comminution) to achieve these reductions. This indicates significant constraints within the sector-based approach.

There are, however, two other methods for setting science-based targets (SBTs). The "absolute-based" approach assigns a percentage of absolute emissions reductions to individual companies, typically ranging from a 49-72% reduction below 2010 levels. However, this approach may not be ideal for companies expecting growth. The "economic-based" approach, on the other hand, bases a company's share of emissions on its gross profit, resulting in an intensity target (Thomas & Lund, 2018). Despite the existence of accepted methodologies under this approach, SBTi recommends using either the sectoral or absolute-based approaches to ensure the 2°C carbon budget is preserved, as economic-based approaches might not lead to absolute global emissions reductions in the long term. SBTi states that "intensity targets would be considered science-based only if they lead to absolute reductions in line with climate science or are modelled using an approved sector pathway or method approved by the Science Based Targets initiative (e.g., the Sectoral Decarbonization Approach)" (SBTi, 2015; SBTi, 2020).

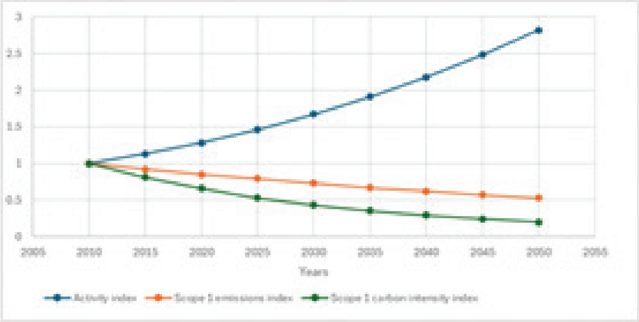

Figure 2 : 87% carbon intensity cut by 2050.

Figure 2 highlights that under the Sectoral Decarbonization Approach, companies are expected to achieve an 87% reduction in carbon intensity by 2050.

Activity Index : This index shows the growth in mining activities relative to the baseline year (2010). A value of 1.00 in 2010 indicates the baseline, and values above 1.00 indicate increased activity over time.

Scope 1 Emissions Index: This index represents the direct greenhouse gas emissions from mining operations, also normalized to the baseline year (2010). A value of 1.00 in 2010 indicates the baseline, and values below 1.00 indicate reduced emissions over time.

Scope 1 Carbon Intensity Index : This index measures the emissions intensity per unit of mining activity, normalized to the baseline year (2010). A value of 1.00 in 2010 indicates the baseline, and values below 1.00 indicate reduced carbon intensity over time. (Recreated from Kirk and Lund., 2018)

Nevertheless, the economic-based approach might be the most practical for the mining industry given the current options. There are several methodologies within this approach, such as the Greenhouse Gas Emissions per unit of Value Added (GEVA), which encourages a 5% annual reduction in GHG emissions per unit of value added from 1990 to 2050; the Carbon Stabilization Intensity target (CSI), recommending a 9.6% annual reduction in intensity over the same period; and the Context-based Carbon Metric by the Center for Sustainable Organizations (CSO), which allocates reduction burdens unevenly based on the location of emitters and the development status of their economies. Companies are encouraged to choose the method that best fits their needs and to remember the importance of setting science-based and ambitious targets, even if these are not officially recognized by SBTi due to the challenges mentioned (Thomas & Lund, 2018).

4. Solutions

Improving energy efficiency in mining operations can significantly reduce carbon emissions. This involves adopting advanced technologies and practices such as high-efficiency motors, automated and remote-controlled equipment, and optimizing haulage and material handling processes. Energy management systems can monitor and control energy use, identifying areas where efficiency can be improved. Implementing these technologies can lead to substantial energy savings and emission reductions.

There are several approaches mining companies can take to improve efficiency and reduce carbon output, including shorter-term, transitional initiatives and longer-horizon initiatives to eliminate GHG emissions.

4.1. Longer-horizon initiatives :

Electricity Supply

For many mining companies, one of the initial steps towards reducing carbon emissions involves improving the electricity supply. This task may vary in difficulty depending on regional regulatory barriers, but it is an especially viable option for mines currently dependent on on-site diesel generators. Understanding energy security risks and considering renewable energy sources can be beneficial. Mining has an advantage over other heavy industries like cement, steel, and chemicals, as a significant portion of its emissions stem from electricity usage.

Solar photovoltaic (PV) technology, coupled with energy storage (ES), is frequently discussed in this context. Although ES is already commercially viable for certain markets and applications, its costs are anticipated to decrease further, which will significantly enhance the integration of renewable energy. ES, often associated with batteries, also includes other forms such as pumped-hydro energy storage (PHES), compressed-air energy storage (CAES), and flywheels. ES can offer mines several benefits, including :

Smoothing the intermittency of renewable energy

Reducing peak demand

Providing backup power and enhancing reliability

The primary motivation for implementing PV and ES projects at mine sites is their economic benefits, rather than the environmental advantages of the power produced. Mines are increasingly recognizing this value, and many have already installed or are in the process of developing PV or PV+ES systems. Notable examples include :

- Gold Fields is completing a 40 MW PV array in South Africa.
- BHP, along with partners, is installing a 13 MW PV array with 1.4 MW/5.3 MWh of storage.
- Sandfire Resources has installed a 10 MW single-axis tracking array with a 4 MW/1.8 MWh lithium-ion battery storage system in Australia.

- Cronimet Chrome Mining SA has installed a 1 MW solar array in 2012, which displaces over 450,000 liters (118.9 thousand gallons) of diesel and 2,000 tons of carbon dioxide annually.
- B2Gold has installed a 7 MW solar PV plant in Namibia.
- IAMGOLD has installed a solar-diesel hybrid 15 MW PV plant in Burkina Faso.

Renewable energy solutions are appealing not only for active mines but also for legacy mines. These sites often have large amounts of unused land with limited direct economic value, yet the mining company remains involved during the reclamation process. If the site is connected to the grid, there may be excess transmission capacity to facilitate power distribution, potentially offering compensation to the mine. Developing renewable resources provides value by repurposing the site for a second productive life. Various technologies can be applied to match the demands and constraints of different electricity markets, offering flexibility. However, for optimal success, renewable projects at legacy sites should be planned well before mine closure.

Additionally, mines can explore power purchase agreements (PPA) or virtual PPAs (VPPA) as baseline comparisons. PPAs and VPPAs generally reduce project risk by having a third party build, own, and operate the renewable system, whether on- or off-site, but may increase project costs to cover the third party's margins. This option can be attractive for large companies with concentrated operations, often with only a small premium.

Mining companies are still learning how to convert what has traditionally been a liability into an asset. For instance, BHP is examining a portfolio of over a dozen legacy mines across North America through its Closed Sites North America initiative to identify the best candidates for low-emissions technologies. Some companies, like ASARCO, have taken significant steps, such as installing a 35 MWp solar array at its Pima mine site in Arizona. Additionally, adopting hydrogen fuel cell technology for powering machinery and haulage, assuming the use of green hydrogen, can be another example of innovative solutions.

Reducing Scope 3 Emission

Given that mining's direct production of greenhouse gas (GHG) emissions is relatively minimal, assisting downstream entities in reducing their emissions can have a significantly larger impact. By measuring and monetizing these solutions, mining companies can generate financial returns that enhance shareholder value. Many mining companies are actively exploring various strategies to address Scope 3 emissions. These include forming innovation joint ventures and research and development partnerships with downstream companies to create new low-carbon processes and products. Specifically, for bulk materials like iron ore, focusing on beneficiation and grade control (such as blast movement monitoring) can notably affect Scope 3 emissions until the steelmaking process is fully decarbonized.

For instance, a study suggests that enhancing the iron content of a 58% Fe low-grade iron ore product by a mere 0.5% could lower emissions at downstream steel mills by roughly 0.75% per unit of hot metal or steel produced. Considering that downstream Scope 3 emissions for lower-grade iron ore products can be over 100 times greater than the Scope 1 and 2 emissions of the mining company, this modest improvement could lead to reductions exceeding the combined Scope 1 and 2 emissions produced by the iron ore mining company itself.

Additionally, higher-grade iron ore products already command premium prices, and carbon pricing could further increase this premium as buyers aim to avoid carbon taxes and other penalties. For example, enhancing a 58% Fe iron ore product to a 58.5% Fe grade could boost the price premium by over US$1 per tonne (from an approximate US$5 per tonne to US$6 per tonne—an increase of around 20%) if steel manufacturers face a carbon price of US$100 per tonne.

Table 3 : Example of Premium Pricing with Carbon Pricing

Iron Ore Grade Improvement	**Price Increase (per tonne)**
58% Fe to 58.5% Fe	US$1 increase (20%)
Zero-carbon 58% Fe iron ore	US$3 per tonne premium
Zero-carbon 66% Fe iron ore	US$3.16 per tonne premium

Crucial to achieving these price premiums is the implementation of precise and verifiable carbon tracking that begins at the mine and extends throughout the entire downstream value chain. As more mining companies adopt these practices, it is conceivable that metal and mineral prices will eventually be determined based on their global carbon footprint or sustainability score. For instance, with a US$100 per tonne carbon price, a steel producer might be willing to pay a premium of US$3 per tonne for zero-carbon 58% Fe iron ore or a US$3.16 per tonne premium for zero-carbon 66% Fe “green” iron ore. However, this is contingent on the buyer’s motivation, which may be influenced by carbon taxes or consumer pressure to purchase such environmentally-friendly products.

Sustainable Mining Practices in Terms of Methane recovery

The mining sector, traditionally viewed as a significant environmental challenge, is now increasingly recognized as essential to the solution. Both investors and consumers are starting to see the industry not only as a primary source of emissions within the value chain but also as a vital supplier of key raw materials necessary for the global transition to sustainable energy.

Adopting sustainable mining practices is critical to mitigating the environmental impacts of mining activities. This involves initiatives such as recycling and reusing water, minimizing waste production, and rehabilitating mined lands. Techniques like dry stacking of tailings, which reduces water consumption and mitigates the risk of tailings dam failures, are gaining traction. Furthermore, using bio-reagents in place of chemical reagents in mineral processing can decrease the toxicity of waste products.

Many mining companies are now embracing their environmental responsibilities by actively working to lower greenhouse gas (GHG) emissions and reduce their overall carbon footprint. The perceived financial benefits are a significant driver behind this shift. Decarbonization presents a revenue opportunity by enabling the mining and sale of essential raw materials like copper, lithium, cobalt, and nickel, which are crucial for the energy transition, or by allowing the imposition of premium prices on low-carbon products. Additionally, decarbonization helps reduce the cost of capital through improved access to sustainability-linked funding from investors focused on environmental, social, and governance (ESG) factors. While mining companies must navigate the interests of various stakeholders - including local communities, governments, regulators, customers, employees, and investors - equity investors often have a significant influence due to the capital-intensive nature of the industry. Moreover, investors are increasingly advocating for decarbonization efforts.

Nearly all major mining companies now have programs aimed at reducing carbon emissions. An analysis by S&P Global Market Intelligence revealed that seven of the ten largest metals and mining companies by market capitalization have committed to achieving net zero for Scope 1 (direct) and Scope 2 (indirect) emissions, or carbon neutrality, by 2050 or sooner (Kuykendall, 2021).

Reducing methane emissions in the mining industry requires a multifaceted approach that leverages advanced technological solutions. This section discusses various technological innovations and practices that can significantly reduce methane emissions from coal mines.

Methane drainage systems are vital for capturing methane from coal seams before it enters the mine’s ventilation air. Optimizing these systems using fuzzy RBF control methods can enhance gas capture efficiency and lower operational costs (Mi, 2013). Automated control systems further improve safety and efficiency by continuously monitoring and adjusting the drainage process based on real-time data (Băbuț *et al., 2017).*

Research indicates that optimizing the design and operation of methane drainage systems can substantially improve their performance. This involves critically analysing and modifying existing manual control procedures to meet stringent legislative requirements and enhance methane capture rates (Băbuț, 2018).

Ventilation Air Methane (VAM) technologies focus on utilizing the low concentration methane present in ventilation air. Thermal flow-reversal reactors (TFRR) and catalytic flow-reversal reactors (CFRR) are effective in oxidizing VAM, converting methane into less harmful substances, and generating energy in the process (Rahimpour et al., 2023; Wang & Zhu, 2021).

Innovative methanotrophic coatings, which can capture and convert methane at ambient temperatures, are applied to ventilation ducts, reducing methane emissions by over 99% in some cases. Although these materials are still under research, they show significant promise for large-scale implementation (Lundberg *et al., 2023).*

Captured methane can be utilized as a fuel for power generation. Gas gensets can convert methane into electricity and heat, providing a valuable energy resource for mining operations and surrounding communities. This approach not only reduces emissions but also enhances energy security and decreases dependence on external power sources (Smirnova *et al., 2022).*

Incorporating methane into absorption refrigeration systems can provide cooling for IT equipment and other critical infrastructure in mining operations. This method uses direct methane combustion to drive refrigeration cycles, further improving energy efficiency and reducing greenhouse gas emissions (Smirnova *et al., 2022).*

Electrification

Environmentally beneficial electrification involves transitioning energy end uses from fossil fuels (such as natural gas, propane, gasoline, diesel, or fuel oil) to electricity to reduce greenhouse gas emissions. Electric motors, when powered by clean electricity sources, tend to be more efficient in terms of emissions, quieter, and require less maintenance than their diesel counterparts. Additionally, electric motors offer significant advantages for underground mining operations. They do not emit harmful fumes or diesel particulate matter and produce less heat, thus reducing the need for extensive ventilation. Companies like Sandvik and MacLean Engineering are pioneering battery- and electric-powered mining machinery, including drills and bolters.

The electrification of mining equipment is a crucial step towards decarbonizing the mining industry. Replacing diesel-powered machinery with electric alternatives can substantially reduce emissions. Battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs) are being developed specifically for mining operations. These electric vehicles not only offer lower emissions, but also reduced operating costs and enhanced performance. Research is also being conducted on the development and use of emission-free explosives to further lessen the environmental impact of mining activities (Kirk & Lund, 2018; Science Based Targets initiative, 2018; Jacobs, Keenan, & Cranmer, 2022; KPMG Assurance and Consulting Services LLP, 2024).

The concept of an all-electric mine is becoming a reality, as demonstrated by Goldcorp's Borden Lake gold mine in Ontario, Canada. Although the project is scheduled for completion in 2019, the objective is to eliminate diesel equipment usage underground entirely. By switching to electric machinery, Goldcorp anticipates saving 7,000 tons of CO2, 2 million liters of diesel, and 1 million liters of propane annually. This shift not only improves Goldcorp's financial performance but also enhances its social license to operate. Running a cleaner mine facilitates the process of obtaining necessary environmental permits.

Trucking/Transport Innovations

The final area ripe for technological advancement is transport, where innovations are driven by the convergence of electrification and automation. Several companies are leading the charge in electrification

(Kirk & Lund, 2018; Science Based Targets initiative, 2018; Jacobs, Keenan, & Cranmer, 2022; KPMG Assurance and Consulting Services LLP, 2024). For instance :

- Liebherr is developing a prototype for a diesel-electric truck set to be commercially available by the end of 2018.
- Komatsu is working on a 45-ton all-electric dump truck equipped with regenerative braking, which capitalizes on the energy generated from moving heavy loads downhill.
- Artisan, a smaller company focused on electric vehicles for underground mining, has recently introduced a 40-ton underground hauler.

Electric vehicles (EVs) are not only more environmentally friendly due to lower carbon emissions, but they also tend to have reduced operation and maintenance costs. This is because electric motors are simpler mechanically, leading to fewer breakdowns, and their fuel—electricity—is generally cheaper. Although EVs currently face the challenge of long charging times, advancements are being made in quick-charge methods and battery swap stations to enable near-continuous operation.

Parallel to the shift towards electric vehicles is the trend towards automation. Rio Tinto is a leader in this field, operating autonomous haulage trucks at four of its mines in Australia and planning to expand to a fifth site by the end of the year. Additionally, Rio Tinto has developed an autonomous rail system called AutoHaul, which successfully completed a 100 km journey in October 2017. Other mining companies, such as Fortescue Metals Group, are also embracing autonomous technology, with Fortescue boasting the world's first fully autonomous hauling fleet at one of its iron ore mines.

While automation might not seem directly related to carbon reduction, it offers significant efficiency benefits. Autonomous vehicles can optimize acceleration and braking for better fuel efficiency and require less maintenance over time. They can also operate continuously, as they do not require breaks like human operators do. Fortescue, for example, increased its hauling productivity by 30% after implementing its autonomous hauling system. Due to the substantial electrical requirements of onboard autonomous systems, these vehicles are well-suited to be either hybrid or fully electric. However, the adoption of autonomous technologies will likely reduce the number of jobs at mining sites, though it may also result in fewer injuries and fatalities. It will be important to consider the impacts on local communities, the mine's social license to operate, and potential regulatory responses.

Improvements in electricity supply, along with innovations in process, technology, electrification, and transportation, all play crucial roles in reducing greenhouse gas emissions at mine sites. In addition to these changes, the mining industry must adopt two fundamental shifts. Firstly, increasing recycling efforts to decrease the need for new resources. Secondly, designing extraction and production methods to maximize on-site resource productivity instead of compartmentalizing functions (Kirk & Lund, 2018; Science Based Targets initiative, 2018; Jacobs, Keenan, & Cranmer, 2022; KPMG Assurance and Consulting Services LLP, 2024).

4.2. Shorter-term initiatives :

Energy Efficiency Improvements

Enhancing energy efficiency within mining operations can play a crucial role in reducing carbon emissions. This can be achieved by integrating advanced technologies and practices, such as high-efficiency motors, automated and remote-controlled equipment, and optimized haulage and material handling processes. Energy management systems that monitor and control energy consumption can help identify areas for efficiency improvements. Adopting these technologies can result in substantial energy savings and significant reductions in emissions.

Mining companies can increase production while reducing greenhouse gas emissions by leveraging various strategies tailored to their specific circumstances. These strategies include integrating renewable energy into their electricity supply, improving mining processes, switching to renewable fuel sources, minimizing waste, and optimizing transportation.

Process Improvements

Not all carbon reduction strategies are tied to electricity usage. Mining companies can also reduce carbon emissions by implementing process improvements aimed at enhancing efficiency. One accessible method for all companies involves using data more effectively to optimize operations (Kirk & Lund, 2018; Science Based Targets initiative, 2018; Deloitte., 2020; Jacobs, Keenan, & Cranmer, 2022; KPMG Assurance and Consulting Services LLP, 2024). Some examples include:

- Advanced asset management strategies that combine operational and inspection data with predictive analytics to determine when equipment needs servicing or replacement. Internet of Things (IoT) devices can generate the vast amounts of data necessary for these advanced analytics. Proper maintenance prevents equipment failures and reduces overall operational costs.
- Unmanned aerial vehicles (UAVs), or drones, can provide various services to mining operations, such as pit and stockpile assessments, site surveying, and planning for blasting and rehabilitation. Compared to traditional tools, drones can perform these tasks more quickly, cost-effectively, and safely. For instance, Freeport-McMoRan uses UAVs for weekly topographic surveys of a copper mine in the Democratic Republic of Congo, a task previously performed by ground surveyors, which required halting mining operations and produced less accurate results.

Technology Improvements

Mines are adopting new technologies that are either more efficient than their predecessors or offer entirely new ways to perform tasks. Emphasis is placed on leveraging technological advancements such as energy storage, digital technologies (IoT, AI, blockchain), and innovative processes to enhance efficiency and reduce emissions (Kirk & Lund, 2018; Science Based Targets initiative, 2018; Deloitte., 2020; Jacobs, Keenan, & Cranmer, 2022; KPMG Assurance and Consulting Services LLP, 2024). Examples include :

- Mines in Nevada have switched from metal-halide lights to LEDs and installed variable-frequency drives on crushers and conveyor belts.
- Rio Tinto developed a more efficient aluminium smelter, which reduced costs and emissions while improving productivity by 40%.
- Biomining, which uses small organisms like bacteria to extract metals from ore, is gaining traction, particularly in remote locations. This method generally has a lower environmental impact and requires less energy than traditional mining practices. Companies such as Codelco and JX Nippon are working to develop and refine biomining techniques.
- Companies and vendors like Anglo American, Rio Tinto, Freeport-McMoRan, Codelco, Komatsu, Caterpillar, and Epiroc are creating new machines capable of cutting through harder rock formations, enabling continuous mechanical rock excavation at more sites. This method is more efficient and predictable than blast-and-drill workflows, requires fewer personnel, can be performed remotely, and operates round the clock.
- Anglo American is enhancing operational efficiency through advanced fragmentation (which reduces the amount of ore sent to high-energy grinding), bulk sorting (which removes less viable rock earlier), and coarse particle recovery (which can float larger particles).

Some solutions offer limited value enhancement, such as divesting coal mining assets and carbon capture, utilization, and storage (CCUS). Regardless of the approach, digital transformation is essential. Net-zero solutions supported by digital technologies can provide cost-effective ways to achieve emissions reductions across various sectors and jurisdictions. For example, recent research by Accenture indicates that by pursuing strategic short-term and next-horizon opportunities, European companies can position themselves to meet the ambitious target of a 55% emissions reduction by 2030 and unlock approximately €28 billion in business value across six sectors—chemicals, cement, iron and steel, battery, pharma, and data centers—by 2025 (Ollagnier, Dijkstra, & Kari, 2021).

5. Strategizing Net Zero Target

5.1. Scope 1 Emissions (Direct Emissions from Owned or Controlled Sources)

Scope 1 emissions, which are the direct greenhouse gas (GHG) emissions from mining operations, primarily arise from the use of fossil fuels in machinery, transportation, and onsite energy generation. These emissions can be addressed by transitioning to cleaner technologies and optimizing operational processes.

Electrification of Equipment

Electric machinery such as Battery Electric Vehicles (BEVs) and Fuel Cell Electric Vehicles (FCEVs) replace diesel-powered counterparts, leading to significant reductions in CO_2 emissions. For instance, Goldcorp's Borden Lake project in Canada, a fully electric mine, is expected to save around 7,000 tons of CO_2 annually by eliminating diesel usage. While the initial investment in electric equipment can be high—an electric haul truck might cost $3 million compared to $2 million for a diesel equivalent—operating costs are generally lower due to savings on fuel and maintenance. Additionally, electric equipment reduces ventilation costs in underground mines, providing further financial benefits.

Alternative Fuels

Adopting low-carbon fuels such as hydrogen or biofuels can serve as a bridge while the industry scales up electrification. For example, Anglo American is piloting hydrogen-powered mine haul trucks as part of their FutureSmart Mining™ initiative.

Methane Capture and Utilization

Methane emissions, particularly from coal mining, are a major contributor to Scope 1 emissions. Technologies such as Ventilation Air Methane (VAM) oxidizers can convert low-concentration methane into energy. For example, Sandfire Resources in Australia implemented a solar array with energy storage, cutting down on reliance on methane-producing energy sources.

Process Optimization

Predictive maintenance, enabled by IoT and advanced analytics, helps reduce equipment downtime and energy consumption. For instance, Freeport-McMoRan uses drones for site surveys, which significantly enhances efficiency and reduces the carbon footprint of its operations.

Implementing energy-efficient practices, such as optimized haul routes, can reduce fuel consumption. Additionally, the use of digital twin technologies to simulate and optimize mining operations can lead to significant energy savings.

5.2. Scope 2 Emissions (Indirect Emissions from Purchased Electricity)

Scope 2 emissions result from the generation of purchased electricity used by mining operations. Reducing these emissions is essential as mining is energy-intensive, relying heavily on electricity for processes like grinding and material handling.

Renewable Energy Integration

Shifting to renewable energy sources, such as solar or wind power, is a primary strategy. BHP, for example, installed a 13 MW solar array with 1.4 MW/5.3 MWh of storage, demonstrating how renewables can be integrated even in remote locations.

While setting up a solar plant can be costly, with installations like BHP's costing around $20 million, the long-term savings from reduced energy costs and carbon pricing can outweigh the initial investment. Over time, solar power is more economical than fossil fuel-based electricity, especially with declining costs of solar technology and energy storage.

Power Purchase Agreements (PPAs)

PPAs allow mining companies to procure renewable energy at fixed prices, providing cost stability and reducing carbon footprints. For example, Anglo American's agreement with a renewable energy provider in South Africa is expected to supply over 70% of its energy needs at a lower cost than traditional sources.

Energy Efficiency Improvements

Implementing energy management systems (EMS) can further reduce electricity consumption by monitoring and optimizing energy use. Upgrades to energy-efficient motors and lighting, like Rio Tinto's switch to LED lighting, have shown reductions in energy use and cost.

5.3. Scope 3 Emissions (All Other Indirect Emissions in the Value Chain)

Scope 3 emissions, which include all other indirect emissions from the mining value chain, are the most challenging to address. They account for emissions from activities like material transportation, processing, and product use. These emissions often represent the largest portion of a mining company's carbon footprint.

Supplier Collaboration and Accountability

Mining companies should actively engage with suppliers to encourage the adoption of sustainable practices. This can involve developing and implementing sustainability criteria in procurement policies. Suppliers should be required to report on their GHG emissions and demonstrate efforts to reduce them. Conducting regular audits to assess the environmental performance of suppliers. Offer incentives such as preferred supplier status or financial benefits for those meeting sustainability targets. Providing training and resources to help suppliers understand and implement best practices for emissions reduction. This could include guidance on energy efficiency, renewable energy adoption, and sustainable resource management.

Rio Tinto has set sustainability criteria for its suppliers, requiring them to report GHG emissions and outline reduction initiatives. They provide training programs for suppliers on energy efficiency and sustainable practices.

Optimizing Logistics and Transportation

Transportation is a significant contributor to Scope 3 emissions, especially in the mining industry where materials often need to be moved across long distances. A shift to low-emission transportation modes is the key. Encouraging the use of less carbon-intensive transportation methods such as rail or shipping, which are more efficient than road transport is necessary. Companies can also explore partnerships with logistics providers that utilize electric or hydrogen-powered fleets.

Utilizing advanced logistics software to optimize transport routes, reducing the distance travelled and fuel consumed. Maximizing load efficiency can also decrease the number of trips required, thereby lowering overall emissions.

BHP collaborates with logistics providers to shift from road to rail transportation, reducing emissions per ton-mile. They also utilize advanced logistics software to optimize delivery routes.

Investment in Alternative Fuels

Support the development and use of alternative fuels like biofuels or synthetic fuels for transportation. Mining companies can work with logistics partners to transition to these fuels, which offer lower lifecycle emissions compared to traditional fossil fuels.

Fortescue Metals Group is investing in hydrogen fuel technology for heavy transport vehicles and has partnered with suppliers to transition to biofuels in operational areas.

Promoting Circular Economy and Sustainable Product Design

A circular economy approach minimizes waste and maximizes the use of resources, which can significantly reduce Scope 3 emissions. Mine products should be designed with the end of their lifecycle in mind. This involves enhancing product durability that leads to reducing the frequency of replacement and associated emissions. Using materials that are easier to recycle or have lower embodied carbon can also reduce emission. Companies should establish programs to take back used products for recycling and repurpose materials. This reduces the demand for virgin raw materials, which typically involve high emissions from extraction and processing.

Innovative uses for by-products or waste materials from mining operations, turns potential waste into valuable resources. This reduces the overall environmental footprint of the mining process.

Anglo American is exploring ways to reuse mining waste as construction materials and has developed take-back programs for recycling metals.

Customer and End-User Engagement

The use of products and their disposal at the end of their lifecycle are key components of Scope 3 emissions. Companies need to develop and market products that contribute to a lower carbon footprint in their application. For example, metals used in electric vehicles or renewable energy infrastructure help reduce emissions downstream. Working closely with customers to understand their emissions reduction goals and how mining products can support these objectives. For instance, offer guidance on using materials efficiently or provide services that help reduce waste in the customer's operations.

Providing detailed information about the carbon footprint of products throughout their lifecycle is an absolute necessity. This transparency can help customers make informed decisions and drive demand for low-carbon products.

Vale provides its customers with detailed lifecycle assessments of their iron ore products, helping them understand and reduce emissions in downstream applications like steel production.

Investing in Carbon Offsetting and Removal

While the primary focus should be on reducing emissions, carbon offsetting can play a role in managing unavoidable emissions. Investing in credible/certified offset projects, such as reforestation, renewable energy, or carbon capture and storage. These projects should be verified by reputable third-party organizations to ensure their effectiveness. Companies need to explore and invest in technologies that capture and store carbon emissions, either directly from the air (Direct Air Capture) or from industrial processes.

Glencore invests in reforestation projects to offset unavoidable emissions and is exploring carbon capture technology for its operations.

Enhancing Collaboration and Advocacy

Scope 3 emissions reduction often requires industry-wide collaboration. Joining or establishing industry consortia focused on reducing Scope 3 emissions helps in knowledge gather and sharing. Shared knowledge and resources can accelerate the adoption of best practices across the sector.

Advocating for policies that support emissions reductions across the value chain, such as incentives for renewable energy, regulations on transportation emissions, and circular economy initiatives also helps lower emissions.Investing in R&D for downstream innovations can be expensive initially. However, the long-term benefits, such as access to green premiums and reduced carbon taxes, can significantly enhance financial returns. For instance, the cost of improving iron ore quality is offset by the premium pricing and lower carbon tax burdens.

5.3.1. Challenges in Reducing Scope 3 Emissions

Complex and Fragmented Supply Chains is one of the most significant challenges in addressing Scope 3 emissions is the inherent complexity and fragmentation of supply chains. The mining industry relies on a diverse network of suppliers, transporters, and downstream users, making it difficult to trace and manage emissions comprehensively. This complexity is exacerbated by the geographical spread and varied operational scales of entities involved, ranging from large multinational corporations to small and medium enterprises (SMEs).

Mining companies often face challenges in exerting influence over their suppliers, particularly those that are smaller or located in regions with less stringent environmental regulations. Suppliers may lack the resources or motivation to adopt sustainable practices, resulting in persistent high emissions within the supply chain.

Transportation constitutes a significant portion of Scope 3 emissions in the mining sector. Inefficiencies in logistics, coupled with reliance on high-emission transportation modes such as road freight, contribute substantially to the overall carbon footprint. In India, infrastructure limitations further compound this issue, leading to higher emissions and logistical challenges.

Emissions associated with the use of mining products, particularly metals used in industries such as construction and automotive, and their eventual disposal, represent a major challenge. The lack of mechanisms to track and mitigate these downstream emissions complicates efforts to address the full life cycle impact of mining activities.

A significant barrier to reducing Scope 3 emissions is the lack of awareness and engagement among stakeholders across the supply chain. Many suppliers and downstream users do not fully understand their emissions profiles or the benefits of implementing reduction strategies.

SMEs within the supply chain often encounter financial barriers that prevent them from adopting sustainable technologies and practices. The high initial investment costs associated with emissions reduction measures can be prohibitive, limiting their capacity to contribute to Scope 3 reduction goals.

Strategies to Overcome Scope 3 Emissions Challenges

Strengthening collaboration across the supply chain is critical. Mining companies can build partnerships with suppliers and downstream users to promote knowledge sharing, joint initiatives, and alignment on sustainability goals. Establishing clear communication channels and collaborative frameworks will facilitate the implementation of emissions reduction strategies.

Developing comprehensive data collection and reporting systems is essential for tracking emissions across the supply chain. Leveraging digital tools and platforms to enhance transparency and standardize reporting practices can significantly improve emissions management.

Mining companies can incentivize suppliers to adopt sustainable practices by integrating sustainability criteria into procurement processes and offering technical and financial support. Initiatives such as preferred supplier programs and capacity-building workshops can drive greater compliance and innovation in reducing emissions.

Addressing transportation emissions requires a shift towards more efficient logistics solutions. This includes adopting low-emission transportation modes such as rail and shipping, optimizing routes through advanced logistics software, and collaborating with logistics providers that utilize electric or alternative fuel vehicles.

Encouraging the adoption of circular economy principles, such as product design for durability, recyclability, and take-back programs, can significantly reduce downstream emissions. Mining companies can collaborate with downstream users to enhance the lifecycle management of their products and reduce waste.

Stronger regulatory frameworks that mandate emissions reporting and incentivize sustainable practices are essential for scaling emissions reduction efforts. Advocacy for policies that support renewable energy adoption, low-emission transport, and circular economy initiatives will further enable the mining sector to achieve its decarbonization targets.

Providing access to green financing options, such as low-interest loans and subsidies, can alleviate the financial burden on SMEs within the supply chain. Partnerships with financial institutions and development of targeted financial products can support the widespread adoption of sustainable practices.

Conclusion and the Road Ahead

Decarbonising the Indian mining industry is a multifaceted challenge that requires a combination of technological innovation, sustainable practices, and supportive policies. By improving energy efficiency, integrating renewable energy, adopting sustainable mining practices, and electrifying mining equipment, the industry can significantly reduce its carbon footprint. Collaborative efforts and strong regulatory frameworks are crucial to achieving a sustainable and environmentally friendly mining sector in India.The way ahead involves a collaborative effort between the government, mining companies, and stakeholders to ensure that the sector not only meets the growing demand for minerals and metals but does so in an environmentally responsible and sustainable manner.

1. **Policy Support and Regulation :** Government policies and regulations play a pivotal role in driv-

ing the decarbonization of the mining sector. Enhanced regulatory frameworks, incentives for renewable energy adoption, and stringent emission reporting standards can accelerate the transition.

2. **Investment in R & D:** Continuous investment in research and development is essential for discovering and implementing new technologies that can further reduce emissions. Collaborations with academic institutions and global partnerships can bring innovative solutions to the Indian mining industry.
3. **Stakeholder Engagement :** Engaging with stakeholders, including local communities, investors, and environmental groups, is crucial for sustainable mining. Transparent reporting and proactive community engagement can enhance the industry's social license to operate.
4. **Leveraging Digital Technologies :** Digital transformation can provide cost-effective ways to achieve emissions reductions. Technologies like the Internet of Things (IoT), artificial intelligence (AI), and advanced data analytics can optimize mining operations, reduce energy consumption, and improve overall efficiency.

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