

Optimization of Land Use and Sustainability in Open-Cast Mining in India: A Case Study of Manganese, Limestone, and Granite-Granted Mining Leases

Ahmed K. S. Dalbon^{1,2*}, Edupuganti N. D. Rao¹, K. Satyanarayana Reddy¹, Adibhatla S. Ram¹

¹ Department of Geology, College of Science and Technology, Andhra University, Visakhapatnam 530003, AP, India

² Department of Geology, Sudan University of Science and Technology, Al-Mogran, Khartoum, Sudan

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Abstract

Effective utilization of mining lease areas is vital for sustainable opencast mining. However, there is limited quantitative evidence to determine if lease size sufficiently accommodates both a mineral deposit and land-use objective. This study offers a comparative land-use analysis of adequacy and spatial efficiency in leased mining, based on differences in models across granted leases in three open-cast mines: metallic manganese, non-metallic limestone, and other dimension-stone granite areas. While focused on India, the findings are applicable beyond national regulations and have broader relevance to open-cast mining. The approach combines statutory mine plan data with spatial analysis techniques to estimate land use, mining activities, waste dumps, environmental buffers, and remaining land. Land-use metrics are employed to compare geometric and mining methods, assessing their impacts on spatial demand and reclamation potential. Results reveal a notable difference: limestone mining demonstrates the highest land-use efficiency, whereas manganese and granite require more land for waste disposal due to the discontinuity of ore bodies and poor block recovery, respectively. Moreover, lease adequacy is more closely associated with land-use efficiency and waste footprint than with lease size. The study introduces a transferable model for evaluating mining lease design based on land-use efficiency rather than fixed-area standards. The method enhances mine planning and progressive reclamation and supports land management strategies that promote sustainable practices, thereby benefiting regulators and mining professionals across various geological and institutional settings.

Keywords: Open-cast Mining; Ore Geometry; Mining Plan; Mine Closure; Land Use.

Introduction

Mining is a vital part of the Indian economy and supplies resources for various sectors, including large-

scale industries. The MMDR Act, 1957, and its amendments regulate the granting, renewal, and operation of mining leases (1). Mining leases are the most common type of license issued in India. They may be

* Corresponding Author; Tel: +919100624310; Email: ibndalbo.rs@andhrauniversity.edu.in

granted for both metallic and non-metallic minerals, with key exceptions including atomic minerals and hydrocarbons. These leases are typically for a fixed duration. They are subject to regulations aimed at limiting productivity, promoting conservation, ensuring orderly resource development, protecting the environment, and guiding land-use planning. Geological potential, accessibility, geophysical factors, and socio-environmental constraints define land lease areas. The size of a lease plays a significant role in the feasibility of mining operations, operational efficiency, and environmental impact.

India accounts for only 2.50% of the world's land area, yet it is home to 16.70% of the global population. The per capita availability of agricultural land has fallen to less than 0.3 hectares, compared to over 11 hectares in the developed world. Earth's natural endowment includes ecosystems (2). Open-cast mining has caused extensive land degradation over approximately 0.26 million hectares (3). Achieving optimal land use and sustainability involves several steps: (1) integrating mine reclamation and closure planning during the initial mine planning; (2) implementing progressive reclamation while mining is active; and (3) ensuring comprehensive mine closure that restores ecosystem services and facilitates productive post-mining uses (3, 4). Mining should be planned with closure and reclamation in mind from the beginning to protect local communities and the environment. Escape routes and post-mining land use optimization: multiple case studies from India and other countries show that landscape-level planning, ecological reconstruction—including soil and water conservation, erosion control, re-vegetation with local species—SWOT analysis (Strengths, Weaknesses, Opportunities, and Threats), and Analytic Hierarchy Process (AHP) can help maximize post-mining land use (5, 6). However, the integration of ecological, social, and economic factors remains incomplete in mine closure planning, with differences in quality and execution observed across mineral sectors and regions (7, 4).

While several studies offer important practical insights, future work, especially longitudinal quantitative studies, will be necessary to assess the long-term effectiveness of different reclamation and closure strategies. Additionally, the literature emphasizes adaptive management, stakeholder engagement, and the use of site-specific ecological indicators to monitor the success of reclamation (5, 3). Waste utilization and tailings recycling of electrolytic manganese residue (EMR) are crucial for environmental safety and land use (8). Existing practices and ideas include adopting green mining approaches whereby by-products serve as energy sources, thereby reducing environmental impact and

improving resource efficiency, which is practically synonymous with sustainable mining (9). Advances in wastewater treatment and resource recovery technologies, such as ceramic membrane filtration and constructed wetlands, also support land closure and post-mining land use (10-12). The objectives of this study are to: i) quantify land use in terms of spatial extent and location within mining leases granted for metallic, non-metallic, and building stone minerals; ii) assess whether the size of granted leases allows mining activities, dumping, and environmental buffers to coexist without conflict; iii) compare how efficiently land under lease is being used among three mineral types grouped by their mode of occurrence; and iv) derive lessons for future land-use planning aimed at developing sustainable mining leasable areas.

The importance of this study lies in its contribution to sustainability and environmental management in mining by analysing awarded lease areas and their uses based on mineral type. The model provides a quantitative method for determining the minimum land area required, which is essential for regulators, mining companies, and environmental planners. Additionally, the study presents new data on the relationship between mineral occurrence and land use. The results will also help decision-makers and stakeholders assess, for future lease awards, whether the land can be brought into operation without harming the environment or local communities. "The case studies are from India, but the land-use assessment framework is species-agnostic and applicable elsewhere, in other countries with open-cast mining. This is based on the interrelated factors of lease geometry, mineral occurrence, and land-use allocation plans, which can be adapted across various mining jurisdictions.

Although extensive research has been conducted on the environmental impacts, land reclamation, and closure plans for open-pit mining, little has been done to quantify, in the present day, the extent of mineral resources and land availability within leased areas. Few comparative studies have examined how lease size relates to operational land-use efficiency and sustainability across mineral types. This knowledge gap is addressed through a systematic analysis of land use for metallic, non-metallic, and building-stone mines under granted leases, to develop a replicable methodology for assessing lease adequacy and promoting sustainable my planning.

Materials and Methods

The primary data were obtained from the technical mining plans submitted to the appropriate licensing agencies for three mines. These mines were selected

based on their mineral type: strata-bound metallic (Manganese Mine), laterally extensive bedded non-metallic (Limestone Mine), and building stone (Granite Quarry; Figure 1). These mining plans include details about the lease area, mining methods, bench and slope geometry, number of pits, production, waste management, and environmental protection. The plans were reviewed to obtain quantitative data on mining activities, including waste dumps, pits, roads, greenbelts, storage yards, water bodies, and undisturbed areas. “The manganese mine data were obtained from an approved 5-year mining plan (2020–2025); the limestone mine data originated from an approved life of mine plan updated in 2019; and the granite quarry data derived from a current 5-year mining plan, which was approved in 2016.” ArcGIS 10.3 was used solely to digitize the study area map.

Field validation was not conducted separately due to legal restrictions on access. Since the mining plans described in this paper are legally required documents filed with government authorities, the data are considered

reliable. Secondary data were collected from the Mines and Minerals (Development and Regulation) Act, 1957 (as amended over time), and the rules issued under this act periodically. This data provides the legal authority to establish criteria, issue leases, and set minimum leasing areas for different minerals. Additionally, a quantitative land-use analysis was performed to compare the proportion of the total lease area for each mining activity. Comparisons among the three mines were conducted to identify land-use patterns associated with modes of occurrence. This process will help improve mining leases in a structured way and then evaluate their adequacy, performance, and environmental impact.

The study is also constrained by the availability of secondary data on mine plan approval and does not account for potential down-dip operational deviations. Socioeconomic effects and the monitoring of post-closure land use have also not been tested in practice and are therefore beyond the scope of this study.

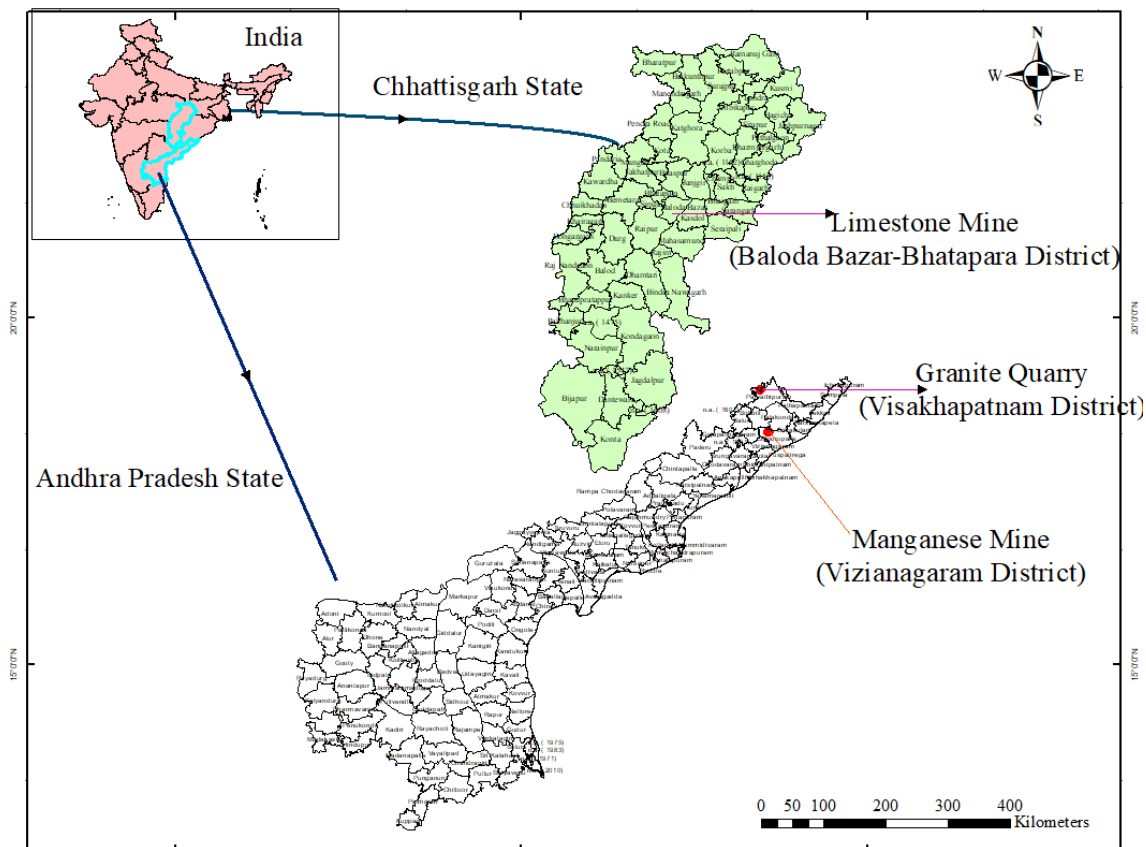


Figure 1. Locations of the studied mines in India (marked with red dots)

Results

The manganese mine

The lease area of the Manganese Mine is primarily government land without forest cover. Manganese ore is mined using fully mechanized open-pit methods. The mine is situated near the Vizianagaram District, Andhra Pradesh, India. The total leasing area of 56.838 hectares is divided into several operational zones, including a broken-up area, a waste dump zone, a mineral storage area, a greenbelt (7.5 meters maintained as a buffer zone), roads, structures, and a virgin area, as shown in Table 1. The leased area is planned to allow manganese ore extraction while minimizing environmental impact. The main section focuses on ore extraction, followed by overburden removal for waste management, and then buffer and environmental zones to protect nearby ecosystems (13).

Geological influence on land use

The manganese mine deposits are in the well-known Vizianagaram–Visakhapatnam manganese belt of the Eastern Ghats. They consist of strata-bound, conformable

layers within the Khondalite–Charnockite metasedimentary succession (Kodurite assemblage). The gangue includes quartz, garnets, and micaceous minerals (14). Geological and genetic evidence support a syngenetic chemical-precipitate origin for the manganese-rich beds, followed by granulite-facies metamorphism and late-stage supergene modification, which contributed to the concentration of the current ore assemblage (15,14). The manganese mineralization appears as lenticular bands, pockets, and irregularly shaped bodies lying parallel to or within the foliation planes (16). Such geometries require a series of pits and subsequently generate more waste relative to ore, resulting in increased land requirements for disposal and buffers.

Land use pattern of the manganese mine site.

Opencast mining activities can alter the landscape within the lease area and disturb surface features in surrounding regions. The entire 56.837-hectare lease area is classified as non-forest government wasteland. Agricultural lands are more than 2 km away from the mine lease area; therefore, there will be no impact on

Table 1. Land use pattern for the five-year plan period (Manganese Mine)

Activities/ Year	Area under mining (Ha)	Overburden/ Waste Dumping (Ha)	Mineral storage (Ha)	Others (Ha)	Green belt (Ha)	Nursery (Ha)	Total area (Ha)	Unutilised area (Ha)
1 st	21.00	17.50	2.00	-	-	1.90	42.58	14.26
2 nd	21.50	17.50	2.30	-	-	1.90	43.12	13.72
3 rd	22.00	17.50	2.30	0.08	3.27	1.90	46.90	9.94
4 th	22.50	17.500	2.30	0.10	5.52	1.90	49.87	6.97
5 th	23.00	17.50	2.30	0.10	7.08	1.90	51.88	4.96

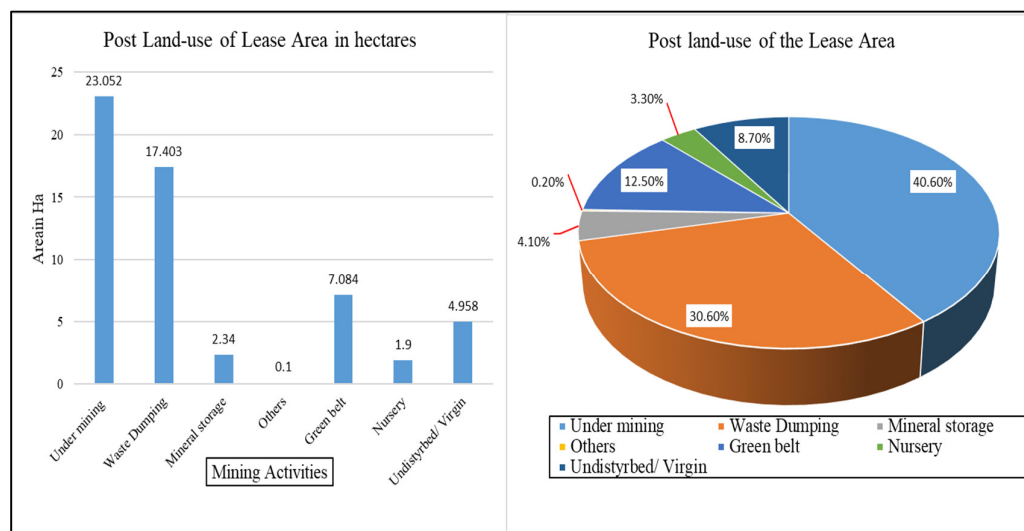


Figure 2. Post land-use pattern of the manganese lease area

farmland. Of the total lease, approximately 23 hectares have been excavated for mineral extraction (about 40.60%), around 7 hectares have been developed as a greenbelt (about 12.50%), about 17.5 hectares are used for dumps (about 30.60%), 1.90 hectares are designated as a nursery (about 3.30%), 2.3 hectares are used for mineral storage (about 4.10%), and 5 hectares remain as undisturbed or virgin land (about 8.70%), as shown in Table 1 & Figure 2.

To ensure scientific relevance, they use derived rather than operational production statistics as land-use indicators. The main factors include the ratios of lease area allocated to mining, waste dumping, greenbelts, and undisturbed lands, as well as the relative intensity of the waste footprint per unit lease area. These measures allow for consistent comparison of production levels across different mines, operational scales, and mineral types.

The Limestone Mine

This limestone mine is a fully mechanized operation located in the Bhatapara District, Chhattisgarh, India. It is a large open-pit mine covering a total lease area of 997.5 hectares of non-forest land. The mine acts as a captive source of raw material for cement production. Limestone is extracted from several benches designed to optimize production while managing waste disposal, environmental concerns, and afforestation within the lease area. The mine has been operational since 1993 and has expanded its output and improved operations over time.

Geological influence on land use

The deposit is a typical high-tonnage, bedded carbonate deposit of the Raipur-Chandrapur succession in the Chhattisgarh Basin and has been exploited by large open-pit quarrying for cement production. The local limestone appears as laterally continuous, generally massive, thick-bedded carbonate horizons with subordinate shaly or carbonaceous partings and a few dolomitic bands. However, it is occasionally weathered near the surface and covered by varying amounts of colluvium, soil, and shallow overburden (17). The new stratigraphic columns have improved our understanding of the geometry and lateral continuity of the limestone bodies, which are crucial for reserve estimation and quarry planning (18,19). The topsoil generated from mining activities is responsibly used to develop the greenbelt. With respect to land-use patterns, those in the buffer zone will not be adversely affected, as mining operations are confined to the mining lease area. Topsoil and overburden disposal are restricted to the core zone along with all other mining-related activities. Nevertheless, land use in the core zone is particularly

important, as it may be affected by mining activities, potential pollution, and waste deposits that could degrade the landscape and scenic beauty. This extensive carbonate slab is amenable to bulk (large-scale) and single-pit quarrying by open-face excavation. Such consistency will permit systematic benching, pit jacking, and backfilling, which are good practices for reclaiming the affected lands for postmining land uses, e.g., water impoundments.

Post-mining land use in the limestone mine.

In the final closure stage, about 33.71% of the lease area will be backfilled with available waste, totalling 179.4 million tons. The floor level of the bottom bench will be maintained between 242 mm and 250 mm above mean sea level (msl), depending on the availability of usable limestone, and the final pit slope will be preserved. Throughout the entire mining period in this lease area, backfilling will continue, and the remaining mined-out section will be converted into a rainwater storage facility. The land use for post-mining activities over 25 years, including mining operations and the conceptual stage in the limestone mine, is detailed in Tables 1 and 2, respectively.

At the final stage of the limestone mine, the active pit area makes up 87.40% of the total lease area. About 1.40% of the lease area is designated for a waste dump. The greenbelt along the roads, with a 7.5 m buffer zone, covers 1.70% of the total lease area. Additionally, 9.60% of the lease area remains undisturbed. Out of 872.00 ha, 565.66 ha has been transformed into a water reservoir, representing 64.90% of the active pit area. The remaining 306.00 ha was backfilled with waste, accounting for 35.10% of the active pit area (Table 3).

The Granite Quarry

The Granite Quarry is located near the Vizianagaram District, Andhra Pradesh, India. It covers a lease area of 9.00 hectares. The mine produces high-quality colored granite, also known as leptynite, which is mainly marketed as "white granite." The lease area is on government land. The mine is situated in hilly terrain where granite occurs in sheet-like formations that extend up to 155 meters above ground level. The operations are designed to extract granite blocks for commercial uses, including rough blocks, slabs, tiles, and monuments. They plan to sell these blocks in both domestic and international markets.

Geological influence on land use

The geology beneath the quarry at Buduruvada features a hilly terrain with NE–SW trending structures, where fine- to medium-grained white granite appears as

Table 2. Land-use pattern of the Limestone Mine Area (%).

Activities	At the end of 5 Years (%)	End of 10 years (%)	End of 15 years (%)	At the end of 20 Years (%)	End of 25 years (%)
Working pit	25.50	40.90	56.44	71.93	87.43
Waste dump site	2.20	2.20	3.19	1.37	1.37
Mineral storage (Sub-grade)	0.30	0.20	0.00	0.00	-
Infrastructure, buildings, etc.	1.00	1.20	0.25	0.25	-
Roads	19.80	2.20	2.22	1.15	-
Railways	0.07	0.00	0.00	0.00	-
Mineral Separation Plant	0.03	0.03	0.00	0.00	-
Township area	0.22	0.22	0.22	0.13	-
Old abundant pit	0.30	0.30	0.30	0.25	-
Screen Reject Dump	0.37	0.00	0.00	0.00	-
Undisturbed area	68.02	52.10	37.37	24.93	9.56
Total			100.00		
Plantation	6.11	7.71	11.73	15.74	33.72

Table 3. Post-mining land use pattern in the limestone my area.

SI No	Particular	Area in Ha	Area in %
1	Working pit area	872.00	87.40
2	Stabilised waste dump (surface) area	13.50	1.40
3	Greenbelt area along the road (buffer zone of 7.5 meters)	16.50	1.70
4	Undisturbed area	95.50	9.60
5	Mined out area developed as a water reservoir area	565.60	64.90
6	Backfilling area	306.00	35.10
7	Total (1+2+3+4)	997.50	100.00
8	Plantation (2+3+6)	336.00	33.71

both sheeted and massive formations, along with boulder outcrops (20). A broad exposure of mainly massive, blocky white granite contains brown ferro-garnet specks within a pale groundmass and is locally marketed as "white/colour granite." The regional geology aligns with the Eastern Ghats terrain, part of a high-grade Archaean-Proterozoic metamorphic belt. Quarry documentation includes details on topography, sheetrock positions, structural orientations, and proposed benching, suitable for small- to moderate-scale dimension stone extraction (20). Lithological data, cross-sections, and reserve estimates reported for dimension-stone quarries within the Eastern Ghats granulite complex are incorporated into the mining plan. The granite quarry primarily targets dimension stone and has minimal overburden, with exposed sheeted or massive rock bodies on the surface. Although recovery rates are high, the block recovery rate is low, resulting in significant waste and considerable effort required for disposal, despite the small lease area.

Mining operation

Garnet quartz-feldspathic gneiss (leptynite) comprises most of the deposit. This type of rock forms through high-grade granulite facies metamorphism. The granite in this area is white to grayish-white, with fine- to medium-grained texture and brown garnet inclusions. It

polishes easily. Large blocks can be quarried from the site because there are few fractures or seams. The quarries use the open-cast method, employing a wire saw to extract blocks of stone, with a jackhammer used to split them into smaller pieces. The quarry is expected to yield 12,000 m³ of granite (approximately 36 years at a constant extraction rate) if demand and depletion rates remain unchanged.

The mining project will comply with environmental laws, waste management practices, dust control measures, and the creation of a greenbelt forest along the lease boundary. Because granite sheetrock is exposed, no overburden removal is necessary to minimize environmental impacts. However, about 76.00% of the extracted material is waste that cannot be sold. This waste is managed systematically and disposed of in authorized waste areas. The total volume of commercial granite that may be sold and the waste produced in the first five years are expected to be 59,180 m³ and 187,415 m³, respectively. The waste will be recycled for alternative uses, such as building materials. Current efforts to rehabilitate and support dump slopes with these sparse plant covers should enhance the sustainability of environmentally sensitive quarrying practices. The leasehold for the first 5 years included an undisturbed

area of approximately 5.6955 hectares, representing 63.33% of the total area. This land is preserved, and the air and water quality are protected for future development, environmental restoration, or other uses. The undisturbed area shrinks to 0.075 hectares over the 20-year lease period. This decrease is attributable to progressive land-use change for mining and related activities. The portion of the original undisturbed land that remains undisturbed at the end of the lease is small. Most of the land is then used for active mining, waste disposal, and reclamation. (Table 4; Figure 3)

Discussion

This study provides a comparative land-use analysis of three distinct open-cast mining scenarios—metallic (manganese), non-metallic (limestone), and dimension stone (granite)—to evaluate mining-lease sufficiency and land-use effectiveness. The discussion integrates how mineral occurrence, deposit geometry, and mining technology collectively influence spatial land

requirements within granted leases, rather than treating these factors as separate site descriptions. Ore extraction is vital within the lease area because it directly affects the mine's production capacity. However, mining occurs in stages, which helps reduce environmental impact (21). Progressive mine closures can facilitate long-term reclamation of the area, reducing land damage and loss (22). The leased area appears adequate for the current mining operation, as the mine uses a staged mining method to minimize environmental damage by preventing overmining.

Comparative productivity of land use for various mineral types

Significant differences are evident in land-use distribution among the three mines (Table 5). The limestone mine has the largest active mining area, covering 87.40% of the total lease area, which reflects the laterally consistent, thick-bedded nature of the carbonate deposit. This setup supports extensive, single-pit operations with reliable benching and systematic backfilling, enabling efficient spatial use despite the large

Table 4. Land use distribution of the Granite Quarry.

Activities	LA based on a 5-year plan period		LA over a 20-year lease period	
	Area in (Ha)	Percentage of total LA	Area in (Ha)	Area in %
Mining Area	2.30	25.67	4.60	51.78
Waste Dump Area	0.75	8.33	3.00	33.33
Roads	0.06	0.65	0.60	6.67
Site Services	0.01	0.06	0.01	0.06
Greenbelt	0.18	2.00	0.72	8.00
Undisturbed Area	5.70	63.33	0.08	0.83
Total Area	9.00	100	9.00	100.00

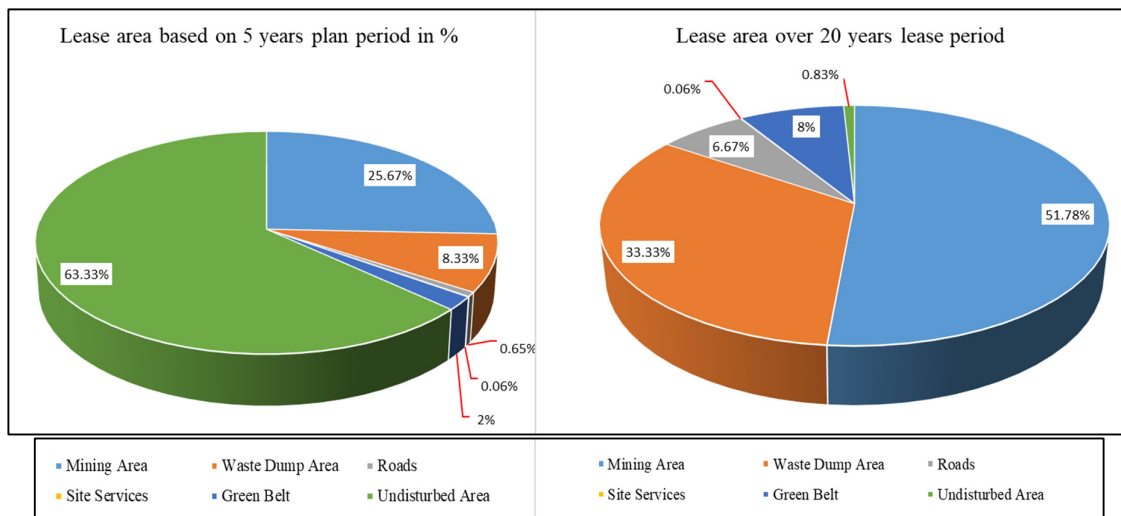


Figure 3. Granite Quarry uses land based on a 5-year plan period and a 20-year lease period.

Table 5. Land-use comparison in mining operations across the three mines.

Mines	Manganese (%)	Limestone (%)	Granite (%)
Activities			
Mining Area in	40.60	87.40	51.80
Waste Dump Area	30.60	1.40	33.30
Greenbelt	12.50	1.70	8.00
Undisturbed area	8.70	9.60	0.80
Others	7.60	0.00	6.10

overall lease size. Conversely, the manganese mine allocates a slightly smaller percentage of its lease area to active mining (40.60%) and a larger portion to waste disposal (30.60%). This pattern is closely linked to the discontinuous, lenticular shape of strata-bound manganese deposits, which require several pits and produce more waste per unit of ore. As a result, additional space is needed for waste storage and buffer zones to maintain operational and environmental stability. The granite quarry illustrates a tertiary land-use concept. Although over half of the lease area (51.80%) is dedicated to extraction, waste disposal still accounts for a significant portion (33.30%) due to the lease's limited size. This reflects the fundamental nature of dimension-stone quarrying, which often has low recovery rates compared to minimal overburden. Consequently, land-use pressure remains high even for small leases, and lease suitability is assessed not only based on available space but also on material recovery efficiency.

Waste footprint and ecological buffers

Waste management plays a vital role in the efficient use of land across all types of mining. Both manganese and granite mining exhibit high waste-to-product ratios, which greatly increase the land required for waste disposal and stabilization. In contrast, the limestone mine reduces waste-related land pressure through regular backfilling, turning excavated areas into water reservoirs. There is substantial variation in the distribution of greenbelt land across mining companies. The manganese mine dedicates most of its land to green belts (12.50%), while the limestone mine allocates only 1.70% for closure. These differences highlight the challenge of developing a universal buffer policy and suggest that planning should be tailored to site-specific factors such as mining activity, dust generation, and waste exposure, rather than relying on fixed legal standards.

Implications for lease adequacy and mine planning

The comparison results suggest that lease fitting is distinct from lease size. Large leases are subject to land-use inefficiencies when waste management and reclamation are not properly coordinated. In contrast, smaller ones can remain viable if mining layout, phased

extraction, and reclamation are carefully planned. The findings indicate that regulatory frameworks should go beyond standardized lease norms and incorporate land-use efficiency metrics, including mining area ratio, waste footprint, buffer requirements, and post-mining land rehabilitation potential.

Global Importance of the Framework

Though the case studies focus on India, the analytical framework used in this research is applicable globally. Features like deposit geometry, mining processes, waste generation, and land-use allocation are common in open-pit mining worldwide. The proposed comparative land-use evaluation method can be applied to mining leases across diverse geological and regulatory settings, providing a flexible tool for assessing lease design and sustainability performance worldwide.

Conclusion

This study demonstrates that effective utilization of mining lease areas depends primarily on mineral association, mining techniques, waste generation, and reclamation strategies. A detailed comparison of manganese, limestone, and granite mining permits indicates that optimal planning accounts for deposit characteristics and prioritizes land use by deposit type rather than permit size alone.

The limestone mine demonstrates that laterally extensive deposits can yield high land-use efficiency, supported by relatively large working pits, systematic backfilling, and the conversion of excavated areas into water reservoirs after mining. The manganese operation illustrates the spatial challenges associated with non-continuous ore bodies, which require storing larger volumes of waste to meet dumping and environmental clearance requirements. The granite quarry illustrates the challenges small dimension stone operations face in maintaining viability amid low recovery rates.

At the management level, the findings suggest that land-use sustainability factors, including the percentage of active mining area relative to the waste footprint, buffer requirements, and post-closure land use, could guide the layout of mining leases. Incorporating

progressive reclamation and phased extraction into mine planning from the beginning can help minimize long-term land disturbance. The development of green belt perimeters and buffer zones should be determined by mining pressure and environmental sensitivity, rather than by arbitrary spatial criteria.

Our main conceptual contribution to this study is to reposition lease adequacy as an issue of operational and spatial efficiency, rather than merely a regulatory or area requirement. In this context, "responsible land use planning" entails integrating geological constraints, operational sequences, waste recycling, and post-mining landscape rehabilitation early within a unified spatial framework. Incorporating these planning principles enables us to optimize environmental performance, land sustainability, and compatibility with mine jurisdiction requirements across various mining jurisdictions worldwide.

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