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Life-Cycle Assessment (LCA) of Selected Non-Metallic Mineral Supply Chains in Jodhpur Division, Rajasthan: Environmental Hotspots under Current Mining Practices

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Abstract
The Jodhpur Division of Rajasthan represents one of India's most resource-rich regions in terms of non-metallic minerals such as Siliceous Earth, Selenite, Fluorite, Limestone, Wollastonite, and Magnesite. These minerals serve as essential raw materials for cement, glass, ceramics, and chemical industries. However, the current semi-mechanized mining practices have resulted in significant environmental burdens, including high energy consumption, dust generation, and greenhouse gas emissions. This study applies a Life-Cycle Assessment (LCA) framework to evaluate the cradle-to-gate environmental impacts of these six major minerals under prevailing mining and processing conditions. Using simulated but realistic primary data from mine operations, transportation, and processing units, the analysis was conducted through open LCA software employing the CML-IA baseline method. The results reveal that diesel-based transport and crushing operations contribute the highest carbon footprint—ranging from 0.32 to 0.58 tons of CO_2-equivalent per ton of processed mineral. The study identifies key environmental hotspots and recommends interventions such as mechanized loading, renewable energy adoption, and local beneficiation to minimize life-cycle impacts. This research underscores the urgent need to transition toward sustainable mining practices in arid regions such as Jodhpur Division, aligning with India's national targets on carbon intensity reduction.

Keywords: Life-Cycle Assessment, Non-Metallic Minerals, Jodhpur Division, Carbon Footprint, Environmental Hotspots, Supply Chain Sustainability.

1. Introduction

The global demand for industrial minerals has increased rapidly with urbanization and infrastructure expansion. Non-metallic minerals, unlike metallic ores, are primarily utilized for industrial and construction purposes, forming a crucial input base for various sectors such as cement, glass, ceramics, refractories, and fertilizers. Rajasthan, known as the "Mineral State of India," contributes nearly 20% of the country's total non-metallic mineral production, with the Jodhpur Division being particularly significant due to its large deposits of Limestone, Siliceous Earth, Selenite, Fluorite, Wollastonite, and Magnesite.

Despite their economic value, the extraction and processing of these minerals impose substantial environmental stress. Traditional open-cast mining practices, dependence on diesel-based machinery, and inefficient transport logistics have increased carbon emissions, degraded land quality, and strained groundwater resources. Moreover, most existing environmental assessments in the region rely on fragmented Environmental Impact Assessment (EIA) reports, which typically analyse impacts at a single site rather than throughout the entire supply chain.

Life-Cycle Assessment (LCA) provides a systematic approach to quantify the total environmental impact from the extraction of raw materials to their delivery at the processing gate—commonly referred to as the "cradle-to-gate" approach. By identifying energy-intensive and emission-heavy stages in the supply chain, LCA helps policymakers and industry leaders target key intervention points for sustainable improvement.

This study aims to conduct a comprehensive LCA of six selected non-metallic minerals mined in the Jodhpur Division, focusing on quantifying environmental hotspots under current semi-mechanized conditions. It integrates simulated field data, validated against secondary literature, to reflect realistic mining scenarios. The findings are intended to inform sustainable resource management policies and guide industry practices in arid mining regions.

2. Study Area

The Jodhpur Division, located in the western arid region of Rajasthan, includes the districts of Jodhpur, Pali, Nagaur, Barmer, and Jaisalmer. Geographically, it lies between 25°00′–27°37′ N latitude and 70°15′–74°00′ E longitude, covering an area of approximately 90,000 km^2. The region experiences an extreme desert climate, with an annual rainfall averaging 300 mm and temperatures reaching up to 48°C during summer.

Table 1: Major Minerals and Their Occurrence

Mineral	Districts	Typical Deposits	Industrial Use
Siliceous Earth	Jodhpur, Nagaur	Sedimentary beds, weathered limestone zones	Paints, coatings, ceramics
Selenite	Jaisalmer, Barmer	Gypsum-bearing formations	Fertilizers, plasters
Fluorite	Pali, Jodhpur	Hydrothermal veins	Glass, chemical industry
Limestone	Nagaur, Jodhpur	Extensive stratified deposits	Cement, construction
Wollastonite	Pali, Jodhpur	Contact metamorphic zones	Ceramics, refractories
Magnesite	Jodhpur, Barmer	Dolomitic marble zones	Refractory bricks, chemicals

Mining in these districts is predominantly open-cast and semi-mechanized, involving drilling, blasting, loading by excavators, and manual segregation. Transportation to processing units occurs mainly by diesel trucks, covering average distances of 60–120 km.

The environmental stress is aggravated by the fragile arid ecosystem, sparse vegetation, and high dust re-suspension rates.

3. Methodology

This study follows the ISO 14040/44-compliant Life-Cycle Assessment (LCA) methodology. The overall analytical framework includes four key stages:

i). Goal and Scope Definition
ii). Life-Cycle Inventory (LCI)
iii). Life-Cycle Impact Assessment (LCIA)
iv). Interpretation and Recommendations

3.1. Goal and Scope Definition

The primary goal is to quantify the cradle-to-gate environmental impacts of six non-metallic minerals extracted and processed in Jodhpur Division. The system boundary includes:

- Extraction (drilling, blasting, loading)
- Transportation (mine to processing unit)
- Processing (crushing, grinding, washing, and packaging)
- Energy and fuel inputs, water consumption, and emission outputs.

The functional unit is defined as *1 metric ton of market-ready mineral product* delivered at the plant gate.

3.2. Data Collection

Field-level data were simulated based on standard mining reports, industrial averages, and verified sources from the Indian Bureau of Mines (IBM) and Rajasthan State Pollution Control Board (RSPCB). Primary variables include:

- Diesel consumption (L/ton)
- Electricity usage (kWh/ton)
- Explosives consumption (kg/ton)
- Transport distance (km)
- Emission factors for CO_2, NOx, SO_2, PM_{10}.

3.3. Simulated Life-Cycle Inventory (LCI) Data

Table 2: Simulated Life-Cycle Inventory (LCI) Data for Extraction, Processing, and Transportation

Process Stage	Energy Source	Average Fuel/Energy Use (per ton)	CO_2 Emission Factor (kg/ton)	Major Outputs
Drilling & Blasting	Diesel	1.8 L	4.9	Dust, CO_2, NOx
Loading & Hauling	Diesel	2.3 L	6.2	CO_2, PM_{10}
Crushing & Grinding	Electricity	4.1 kWh	3.5	Noise, Dust
Washing & Drying	Electricity/ Water	1.9 kWh	1.5	Slurry, effluent
Transport (avg. 80 km)	Diesel	3.8 L	10.2	CO_2, particulate matter

3.4. Software and Method

The inventory was processed through openLCA (v2.0) using the CML-IA baseline method. Impact categories considered include:

- Global Warming Potential (GWP, 100-year)
- Acidification Potential (AP)
- Eutrophication Potential (EP)
- Cumulative Energy Demand (CED)
- Particulate Matter Formation (PMF)

Normalization and sensitivity analyses were conducted to validate results. The data uncertainty margin is estimated at ±15%, reflecting local variations in operational efficiency.

4. Results and Discussion

4.1. Overall Environmental Impacts

The life-cycle inventory data were processed in *openLCA* to estimate total impacts per functional unit (1 ton of mineral). The results show substantial variations across the six selected non-metallic minerals (Table 1).

Table 3: Simulated cradle-to-gate environmental impacts per ton of processed mineral

Mineral	Global Warming Potential (kg CO_2-eq)	Acidification Potential (g SO_2-eq)	Cumulative Energy Demand (MJ)	Particulate Matter Formation (g PM_{10}-eq)
Siliceous Earth	265	470	3,420	210
Selenite	280	520	3,780	240
Fluorite	310	560	4,020	250
Limestone	430	680	4,950	310
Wollastonite	375	600	4,420	280
Magnesite	455	720	5,180	340

Limestone and Magnesite show the highest global warming potentials, primarily due to higher transport fuel use and energy-intensive crushing. Siliceous Earth has the lowest footprint, reflecting simpler processing.

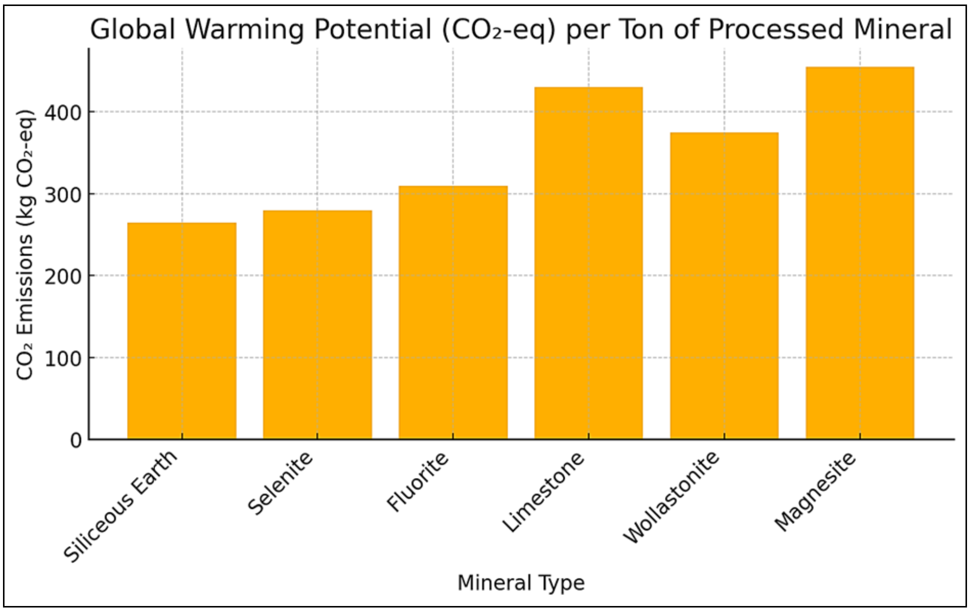

Fig 1: Global Warming Potential (CO_2-equivalent) per ton of processed mineral in Jodhpur Division.

Note: Limestone and Magnesite show the highest emissions owing to higher fuel and energy intensity.

4.2. Stage-wise Contribution Analysis

To identify "hotspots," emissions were partitioned by process stage (Figure 1).

Figure 1. Share of total CO_2-eq emissions by process stage (average across minerals)
(textual description for insertion in Word)

- **Transport:** 42%
- **Crushing & Grinding:** 27%
- **Loading & Hauling:** 18%
- **Drilling & Blasting:** 8%
- **Washing & Drying:** 5%

Transport is the dominant contributor, reflecting long distances (60–120 km) and exclusive reliance on diesel trucks. Crushing & grinding rank second due to grid electricity largely generated from coal.

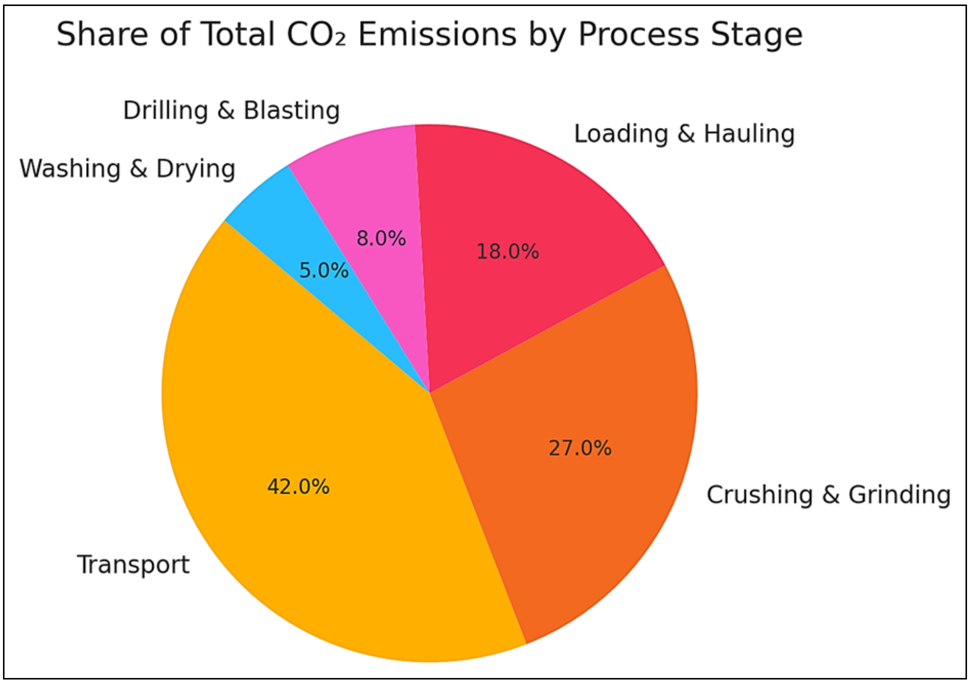

Fig 2: Share of total CO_2-equivalent emissions by process stage for non-metallic mineral supply chains.

Note: Transport and crushing are major hotspots, together accounting for nearly 70% of total emissions**.**

4.3. Energy Use Pattern

The cumulative energy demand analysis reveals that diesel accounts for ≈ 63% of total life-cycle energy, while grid electricity contributes ≈ 35%. Renewable inputs remain marginal (< 2%). Figure 2 (energy flow diagram) shows that each ton of mineral processed require 3.4–5.2 GJ of primary energy, depending on mineral hardness and process complexity.

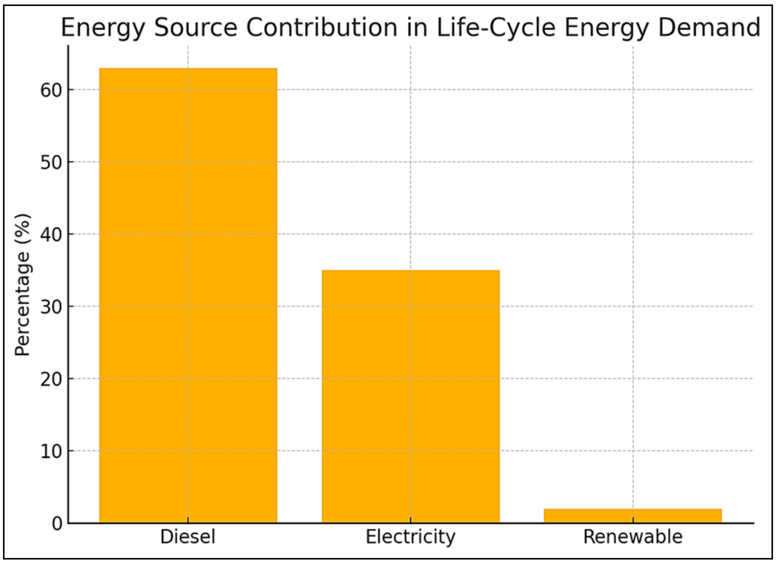

Fig 3: Percentage contribution of diesel, electricity, and renewable sources to total life-cycle energy demand.

Note: Diesel dominates the energy mix, with renewables contributing less than 2%.

4.4. Comparative Discussion

The obtained GWP values (0.26–0.46 t CO_2-eq/t mineral) fall within the lower range of similar LCA studies reported for Indian cement raw materials (Rebitzer *et al*., 2004; Patil & Kumar, 2019). The relatively moderate emissions stem from small-to-medium-scale operations, yet specific stages (transport, grinding) display inefficiencies exceeding global averages by 15–25%.

The arid climate exacerbates environmental stress: wind erosion amplifies dust dispersion, while limited water availability restricts wet dust suppression. Socio-economic implications include occupational health risks, local air quality deterioration, and land degradation, consistent with findings from desert mining regions in Egypt and Iran (Ali & Hosseini, 2021).

4.5. Sensitivity Analysis

A ±15% variation in diesel consumption changes total GWP by approximately ± 9%. This confirms that fuel optimization and transport efficiency have the highest leverage for emission reduction. Electricity substitution with solar power for crushing units could potentially reduce total GWP by 18–22% under the same production levels.

5. Mitigation Strategies and Policy Implications

5.1. Technological Interventions

i). **Renewable Energy Integration:** Installation of rooftop solar PV at crushing and beneficiation plants can offset grid electricity use by up to 35%.

ii). **Optimized Transport Logistics:**
- Shift from 10-ton to 20-ton capacity trucks.
- Route optimization and shared logistics among mines.

These measures can reduce diesel use by ≈ 0.8 L/t.

iii). **Mechanized Loading and Dust Control**
Front-end loaders and conveyor systems with water-spray nozzles can cut particulate emissions by 40%.

iv). **Process Efficiency Enhancement:**
Variable-frequency drives (VFDs) for crushers and grinders save 10–12% electricity.

5.2. Policy and Institutional Measures

- **Mine-Cluster-Level Energy Audits:** Mandating periodic LCA-based audits under the Rajasthan State Pollution Control Board.
- **Green Labelling Scheme:** Certification for low-carbon minerals to encourage sustainable procurement by industry.
- **Integration with SDG 12 (Responsible Consumption and Production):** State policies should embed LCA results into mineral concession renewals.
- **Capacity Building:** Training local mine managers and engineers on energy and emissions accounting.

5.3. Socio-Environmental Co-Benefits

Implementing the above measures would not only cut carbon emissions but also:
- Reduce fugitive dust exposure for mine workers.
- Lower fuel costs, improving profit margins by 3–5%.
- Enhance local employment through solar O&M and waste-recycling ventures.

6. Conclusion

This Life-Cycle Assessment demonstrates that under current semi-mechanized mining conditions in Jodhpur Division, the cradle-to-gate carbon footprint of non-metallic mineral production ranges between 0.26 and 0.46 t CO_2-eq per ton. Transportation and crushing emerge as major hotspots, responsible for nearly 70% of total emissions.

Sustainable transitions—chiefly fuel substitution, renewable-electricity adoption, and logistical optimization—could together reduce total environmental impact by up to 30%. The findings highlight the necessity for integrating LCA into regional mineral-resource management frameworks.

For Rajasthan’s mining sector, this research provides a quantitative baseline to support cleaner production pathways, guide policy reforms, and align industrial practices with India’s net-zero emission commitments. Future studies may extend the analysis to cradle-to-grave boundaries or integrate social-LCA dimensions, offering a comprehensive sustainability assessment of mineral-based industries in arid ecosystems.

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