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A REVIEW ON THE ASSESSMENT OF CONTAMINATED SOIL AND VEGETATION HEALTH AT RED SANDSTONE MINES AREA IN KARAULI DISTRICT OF RAJASTHAN

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Abstract-The Karauli district of Rajasthan, spread over 5,043 square kilometres, represents an area of remarkable geological diversity and mineral wealth. Surrounded by the districts of Dholpur, Bharatpur, Dausa and Sawai Madhopur, Karauli is particularly known for its rich red sandstone deposits, which have supported extensive quarrying and mining for decades. The sandstone in the district, characterized by its fine texture and reddish-brown colour, forms the backbone of local industry and architecture, and contributes significantly to the state's economy. Along with this economic prosperity, however, Karauli has faced increasing environmental challenges – primarily soil pollution, vegetation degradation and contamination of water bodies – resulting from unregulated mining and limited environmental management. Within this broader framework, the red sandstone quarries of Karauli exemplify the tension between economic development and environmental sustainability. Extraction processes involving blasting, quarrying and transport disturb the natural soil profile, accumulate heavy metals such as lead, cadmium, arsenic and chromium and expose surrounding ecosystems to pollution. These pollutants negatively affect soil fertility, reduce vegetation health and threaten agricultural productivity in nearby rural settlements.

The review article focuses specifically on the assessment of environmental impacts of sandstone mining in the Karauli region. It highlights Rajasthan's extensive quarrying activities and emphasizes the need for sustainable mining to protect soil and vegetation health. The study adopts a mixed methods approach, integrating quantitative techniques such as soil sampling, laboratory testing and statistical analysis with qualitative observations of field and ecological conditions. The selected study area, Bhauapura-Ratiapura, , Kasara, Chobe ki Guwari, Mokanpura- Berda , Bhakari and control sites such as Suroth in Karauli. has been analyzed for its soil composition and vegetation response to heavy metal pollution. Various chemical and analytical techniques are used to determine the concentrations and forms of metals such as lead, chromium and cadmium. Data interpretation reveals the extent of pollution and its impact on the local ecological balance. Comparative tables provide a clear understanding of metal distribution and bioavailability in soil samples. This article reviews previous literature on sandstone mining and its environmental impacts. Finally, it concludes by recommending continued monitoring, eco-rehabilitation and sustainable practices to reduce soil erosion and preserve vegetation health in the red sandstone mining areas of Rajasthan.

Keywords- Contaminated soil, Red sandstone mines, Soil assessment, Vegetation health, Heavy metals, Mining pollution, Land degradation, Mine waste, Sustainable remediation.

I. INTRODUCTION

Mining is one of the primary development activities of an economy. The development of any industries of a nation largely depends on the availability of mineral resources, quality of mineral resources, and the level of technology used to harness these mineral resources. Countries with the substantial amount of good quality mineral resources have the chance of achieving faster economic growth (Naik and Basavaraj, 2013).

Minerals are valuable natural resources, but they are finite and non-renewable. They constitute the vital raw materials for many industries and are essential for economic development. The history of mineral extraction in India dates back to the days of the Harappan civilization. The availability of the minerals with abundant rich reserves has made the mining sector in India conducive for growth and development. India, endowed with many metallic and non-metallic minerals. The mineral production has grown both in quantity and value. India produces as many as 87 minerals; which include four fuels, ten metallic and 47 non-metallic, three atomic and 23 minor minerals (GOI, no date a).

Mines in India can be divided broadly into three categories: the public sector mines, the private sector mines which are large in number, and smaller mines and quarries. Quarries are similar to an open-pit mine from which stones are generally extracted. The workers in the public sector mines are mostly employed directly by the enterprises. In the privately owned smaller mines and quarries, private contractors are engaged. However, in smaller mines and quarries, it has been found that employers generally do not implement any social security laws and schemes (GOI, 2002).

Small-scale mining and quarrying are expanding rapidly, often with no control, in many developing countries. These mines employ many women and children in dangerous situations. Studies have found that the workplace fatality rate is 90 times higher than the mines in industrialized countries. Employment in these mines is dangerous as 80 percent of small-scale mining falls outside any legal or regulatory framework (ILO, 1999). One of the reasons for the rapid expansion of such mines is that it enables employment opportunities with small capital and a low level of skills, along with seasonal employment of workers.

The minerals classified as (i) major minerals and (ii) minor minerals. The minor minerals as defined under section 3(e) of the Mines and Minerals Regulation and Development (MMRD) Act, 1957 includes building stones, slate, sand etcetera while major minerals are coal, manganese ore, iron ore, bauxite, etcetera (GOI, no date b).

The small operational mines a characteristic of the mining industry in India reported mineral production [excluding minor minerals, petroleum (crude), natural gas and atomic minerals] of about 4128 such mines. Of these mines, Madhya Pradesh has 697 mines followed by Tamil Nadu (543), Gujarat (467), Andhra Pradesh (462), Karnataka (393), Odisha (350), Jharkhand (164) and Rajasthan (163). Most of the mines (93percent) were private sector mines. As for mineral wise distribution of mines, 2015 were of limestone mines, followed by Iron ore mines (713), bauxite mines (372), and manganese ore (321) mines (IBM, no date b).

A. *Quarrying and Mining in Rajasthan*

Rajasthan, renowned as the "Land of Kings," is a state steeped in history, culture, and breathtaking landscapes. Yet, amidst its cultural riches, Rajasthan also shines as a beacon in the realm of quarrying and mining, carving out a niche as a powerhouse in India's mineral industry. At the forefront of this sector stands Hindustan Zinc, a titan headquartered in the regal city of Udaipur, Rajasthan. This industry giant not only propels the state's economy forward but also boasts the distinction of being India's sole integrated producer of zinc, lead, and silver, commanding a prominent position on the global stage.

Hindustan Zinc's footprint spans across various districts of Rajasthan, where its large-scale mining and smelting operations form the backbone of the state's mineral economy. From the rugged terrain of Bhilwara to the sprawling plains of Udaipur, the company's endeavours have left an indelible mark on the socio-economic landscape of Rajasthan, ushering in prosperity and progress to communities far and wide.

The significance of Hindustan Zinc's contributions extends beyond mere economic gains, as it actively engages in initiatives aimed at promoting sustainable development and environmental stewardship. Through its adherence to stringent environmental standards and implementation of innovative technologies, the company endeavours to minimize its ecological footprint while maximizing the benefits derived from its operations.

Moreover, Hindustan Zinc's commitment to corporate social responsibility manifests in various community-centric programs aimed at uplifting the lives of local residents. Whether through education, healthcare, or infrastructural development, the company leaves no stone unturned in its quest to foster inclusive growth and empower the communities it serves.

In essence, Rajasthan's quarrying, and mining sector, epitomized by the endeavours of Hindustan Zinc, exemplifies the state's spirit of resilience, innovation, and progress. As Rajasthan continues to chart its course towards a brighter future, its mineral riches serve as a testament to the boundless potential that lies within its storied lands, beckoning investors and enthusiasts alike to partake in its journey of growth and prosperity.

B. Environmental Considerations and Sustainable Practices

It's encouraging to see the acknowledgment of environmental considerations and the promotion of sustainable practices in Rajasthan's mining and quarrying sectors. Balancing economic development with environmental conservation is Moreover crucial for the long-term well-being of both the region and its inhabitants.

Hindustan Zinc's commitment to sustainable mining practices serves as a beacon of responsible corporate stewardship. By investing in modern technology and processes, the company not only reduces its environmental footprint but also sets a commendable example for others in the industry to follow. Efforts to minimize water consumption, manage waste responsibly, and undertake reclamation projects demonstrate a holistic approach to environmental management, ensuring that the impacts of mining activities are mitigated to the greatest extent possible.

As Rajasthan continues on its path of economic growth, it's imperative that responsible mining practices and sustainable development remain integral to its trajectory. The pie chart depicting the national share of major minerals from Rajasthan underscores the state's significant contribution to India's mineral wealth. Each slice of the pie represents a different mineral, reflecting its proportionate share of the total national production. This visual representation highlights the diversity and abundance of mineral resources in Rajasthan, underscoring the importance of managing these resources in a manner that preserves their integrity for future generations.

By prioritizing environmental conservation alongside economic progress, Rajasthan can pave the way for a sustainable and inclusive future. Through collaboration between government agencies, industry stakeholders, and local communities, it's possible to achieve a harmonious balance between development and conservation. By adhering to stringent environmental regulations and embracing innovative technologies, Rajasthan can ensure that its natural resources continue to fuel prosperity while safeguarding the ecological integrity of the region.

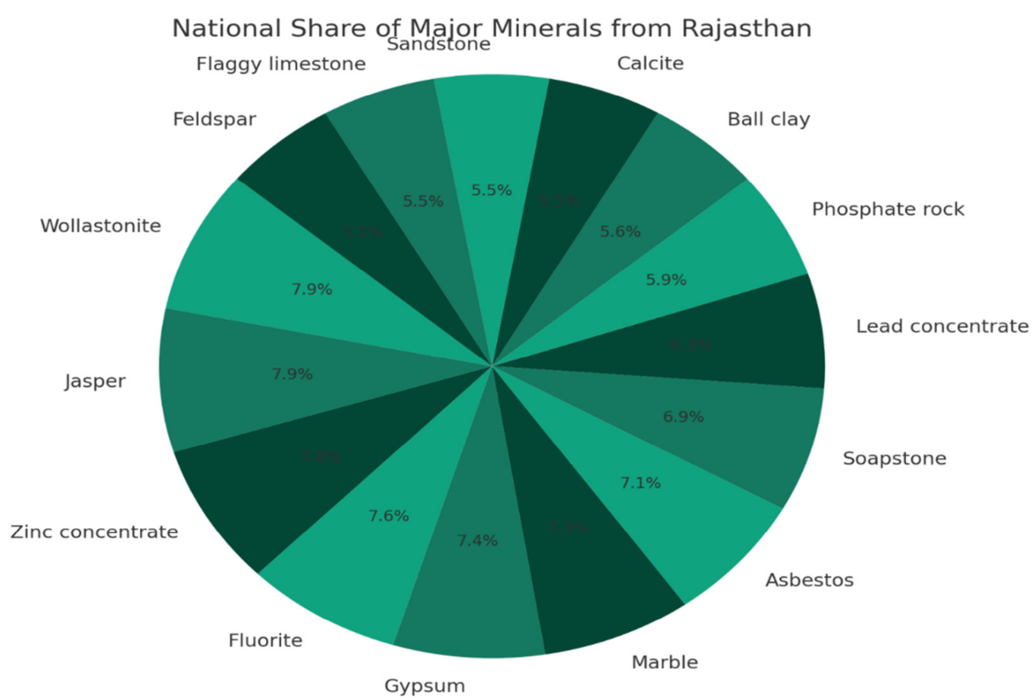

Figure 1: Overview of the Various Minerals Found In Rajasthan

C. ***Quarrying and Mining in Karauli***

The Red Sandstone mines, nestled in the heart of the Karauli district in Rajasthan, India, stand as a testament to both the region's geological richness and its economic vitality. For generations, these mines have been more than mere repositories of minerals; they have been vibrant hubs of activity, driving the local and national economy forward. As Ahmad (2017) aptly points out, their significance cannot be overstated. However, alongside their economic promise, the Red Sandstone mines have also beckoned attention to a pressing issue – the potential environmental toll they exact, particularly in terms of soil contamination and its subsequent ramifications on surrounding vegetation.

One of the most pressing concerns stemming from mining activities in the Karauli district is the pervasive contamination of soil. The very essence of mining involves penetrating deep into the earth's crust, unsettling natural soil layers, and unveiling geological formations previously shielded from exposure. This upheaval wreaks havoc on the delicate balance of soil quality and composition, with far-reaching implications for both the environment and human health. As highlighted by Ma, Ankit, Tiwari, and Bauddh (2022), the methods employed in mining, including drilling, blasting, and excavation, not only disrupt the physical integrity of the soil but also introduce a plethora of pollutants into the surrounding environment.

In the Red Sandstone mines, heavy metals emerge as the primary culprits behind soil contamination, posing significant environmental risks and human health concerns. These heavy metals, inherent to the geological formations being extracted, include lead, cadmium, arsenic, chromium, and others, each with its own toxic properties and potential for harm. As Gaikwad, Aniket, Titirmare, Nihal, and Margal (Prasad, 2023) highlight, the release of these metals into the environment during mining operations. The consequences of soil contamination are manifold and profound, reverberating throughout the ecosystem. Soil serves as the foundation of terrestrial ecosystems, supporting a rich tapestry of plant and animal life. However, when contaminated, it becomes a hostile environment for vegetation, impeding root development, inhibiting nutrient uptake, and compromising plant health and productivity. This disruption cascades through the food web, impacting organisms at all trophic levels and ultimately threatening biodiversity and ecosystem resilience.

Moreover, soil contamination poses significant risks to human health, particularly for communities residing in close proximity to mining sites. Through various pathways, such as direct contact, inhalation of contaminated dust, or consumption of crops grown in polluted soil, toxic substances can enter the human body, causing a myriad of health problems. Children, in particular, are vulnerable to the adverse effects of soil contamination due to their hand-to-mouth behaviour and developing physiology, placing them at heightened risk of neurodevelopment disorders, respiratory ailments, and other health issues.

The adoption of advanced mining technologies and practices can play a pivotal role in mitigating the environmental impacts of mining operations in the Red Sandstone mines area such as Dust Suppression, Efficient Waste Management, Use of Environmentally Friendly Machinery and Equipment, Soil Washing, Phytoremediation, Soil Stabilization.

In conclusion, the contamination of soil arising from mining operations in the Karauli district poses significant challenges to environmental integrity, human health, and sustainable development. addressing the issue of soil contamination in the Red Sandstone mines area requires a coordinated and collaborative effort involving government agencies, mining companies, local communities, and environmental organizations. By implementing strict regulatory frameworks, promoting sustainable mining practices, fostering community engagement, and investing in environmental education and capacity-building initiatives, we can mitigate the impacts of soil contamination, prevent further environmental degradation, and safeguard the health and well-being of present and future generations.

II. REVIEW OF LITERATURE

Campillo-Cora, C., et al. (2025). Effect of heavy metal pollution on soil microorganisms: Influence of soil physicochemical properties. A systematic review: This 2025 systematic review examines how heavy metal contamination affects soil microbial communities, with special attention to how soil physical and chemical properties modulate these impacts. The authors systematically searched databases for studies assessing microbial community composition or function under heavy-metal stress, extracting data on soil pH, texture, organic matter, and other factors. They synthesized findings qualitatively and quantitatively where possible. Across reviewed studies, heavy metals generally suppressed microbial diversity and activity, but effects were strongly mediated by soil pH, organic-matter content, and cation exchange capacity—soils richer in organic content or with neutral pH often mitigated toxicity to microbes.

Damseth et al. (2024) conducted a critical review to assess the impacts of river bed mining on aquatic ecosystems, with a focus on water quality and biodiversity. The study aimed to provide a comprehensive understanding of the ecological implications of this activity, which is essential for meeting construction and infrastructure demands but raises concerns about its adverse effects on natural systems. The methodology involved a systematic search of peer-reviewed literature published between 1985 and 2023, utilizing various scientific databases. Keywords and controlled vocabulary related to river bed mining, aquatic ecosystems, water quality, biodiversity, and remedial measures were incorporated into the search strategy. The review identified degradation of water quality as a primary concern associated with river bed mining. Factors such as sediment release, altered flow patterns, and increased turbidity were found to contribute significantly to water quality deterioration. These changes had cascading effects on physicochemical parameters, impacting nutrient cycles, dissolved oxygen levels, and overall ecosystem health. Furthermore, the review highlighted the diverse challenges faced by biodiversity due to river bed mining. Alteration of riverbed habitats and disruption of natural flow dynamics posed direct threats to various aquatic species. Sedimentation resulting from mining activities further exacerbated biodiversity loss by smothering habitats and affecting reproductive success. The study emphasized the importance of adopting sustainable mining practices, habitat restoration efforts, and the implementation of buffer zones to mitigate the adverse impacts on water quality and support biodiversity conservation. It underscored the need for a holistic approach and robust regulatory measures to ensure the long-term health and resilience of riverine ecosystems amid ongoing development pressures. In conclusion, Damseth et al. provided a nuanced analysis of the impacts of river bed mining on aquatic ecosystems, emphasizing the urgency of addressing water quality degradation and biodiversity loss through sustainable practices and effective management strategies.

An, Q., et al. (2023). The effects of microplastics on heavy metals bioavailability in soils: a meta-analysis. This study synthesizes existing research on how microplastics in soils affect the bioavailability of heavy metals—a timely topic given increasing pollution in terrestrial environments. The authors conducted a meta-analysis by collecting and statistically aggregating data from multiple experimental studies that measured heavy-metal uptake or mobility in soils with and without microplastics. They standardized effect sizes and assessed heterogeneity across studies. The meta-analysis revealed that microplastics significantly modify heavy metal bioavailability—often increasing mobility or uptake—though effects varied by plastic type, soil characteristics, and metal species. The findings underscore the complex interplay between emerging microplastic contamination and traditional heavy-metal pollution pathways.

Hu, B., Guo, et al (2021). Study of soil physicochemical properties and heavy metals of a mangrove restoration wetland: This study evaluates the soil properties and heavy-metal contamination levels in a restored mangrove wetland—vital for assessing ecological health and restoration success.Soil samples were collected across the wetland restoration area. Researchers measured pH, organic-matter, nutrient levels, and heavy-metal concentrations, comparing them to baseline or reference values. The restored wetland soils had high organic matter and moisture content. Heavy metals were generally within acceptable limits, though certain hotspots showed elevated levels—suggesting overall success of restoration, but highlighting the need for ongoing monitoring in areas with higher contamination risk.

Hu et al. (2020) investigated the influence of mining and vegetation restoration on soil properties in the eastern margin of the Qinghai-Tibet Plateau. They selected four land sites: two vegetation restoration sites (restored by Elymus nutans and Picea crassifolia), one non-vegetated mining site, and one native grassland site. Soil samples were collected from these sites, and soil properties, trace metals, and soil enzyme activities were analyzed. The study found that mining caused serious destruction of surface morphology and soil structure, leading to an increase in soil pH (>8.0). Vegetation restoration decreased soil pH compared to native grassland. The site restored with E. nutans showed increases of 48.8% and 25.17% in soil organic matter and total nitrogen, respectively, compared to the site restored with P. crassifolia. Soil enzyme activities decreased after mining, and there were no significant increases in urease, phosphatase, β-glucosidase, and β-1,4-N-acetylglucosaminidase activities after five years of restoration. Additionally, the levels of soil trace metals (cadmium, chromium, mercury, lead, and zinc) after mining were below the Chinese threshold (GB 15618/2018). However, the arsenic content in non-vegetated soil and P. crassifolia-restored soil exceeded the threshold by 22.61 times and 22.86 times, respectively. The study suggests that arsenic-contaminated areas should be accurately identified and treated promptly to prevent further spread. It also recommends selecting plant species tolerant to alkaline soil for vegetation restoration on post-mining lands. Overall, the findings highlight the complex interplay between mining activities, vegetation restoration, and soil properties in fragile ecosystems like the Qinghai-Tibet Plateau.

In conclusion, the study by Kalhor et al. (2019) provided an essential overview of the assessment and remediation of groundwater quality in karst aquifers. It highlighted the unique hydrogeological processes, the complexities of groundwater flow and contaminant transport, and reviewed the most effective remediation techniques and modeling methods for these environments. This comprehensive approach aims to improve the management of karst aquifers, ensuring better protection and sustainable use of these critical groundwater resources.

Kumar and Singh (2016) conducted a geochemical study to assess the quality of mine water in the Western Jharia coalfield area of Jharkhand, India, with a focus on its suitability for drinking and domestic purposes. The study involved systematic sampling during the monsoon season of 2013, collecting eighteen representative mine water samples from both underground (sumps and surface water discharge) and opencast mines. Analysis of the collected samples revealed pH values ranging from 6.8 to 8.3, with electrical conductivity (EC) values ranging from 608 to 1350 µS cm^-1. Total dissolved solids (TDS) ranged from 432 to 1080 mg L^-1, with spatial differences reflecting geological formations, hydrological processes, and mining conditions in the region. The major anions and cations present in the mine water were assessed, indicating the general ionic abundance as follows: HCO3^- > SO42^- > Cl^- > NO3^- > F^- and Mg2+ > Ca2+ > Na+ > K+. The water quality assessment identified total dissolved solids (TDS), total hardness (TH), magnesium, and sulfate as major parameters of concern in the study area, rendering the water unsuitable for drinking and domestic purposes. This study underscores the importance of understanding and monitoring mine water quality to mitigate potential environmental and health risks associated with mining activities in the region.

III. MINING AND PROCESSING OF SANDSTONE

Sandstone is a type of stone made up of grains of quartz and other minerals of uniform size and is often smooth and rounded. The segrains, ranging in size from 2 mm to 120 mm of varying compositions and held together by a cementing material which may be siliceous or ferruginous. The toughness of sandstone depends most lyont he nature of this cementing material. The most common type of sedimentary rock are the sandstone; porous, in nature, the color of sandstone range from dark red to brown, earthy to buff, white, yellow and some other shades. The patterns of the sandstone vary with surface textures and are in earth-toned colors. The variety also depends on the thickness of the bed.

Figure 2: Image of sample of Sandstone Source

Figure 4: Process of breaking stone through chisel-hammer

The mining process starts with removing of topsoil and sub-soil by excavators earlier carried out by manual labour. A jackhammer is used to drill the hard and thick-bedded sandstone under

The beds are split along bedding planes once the chisels penetrate 5-7 centimetres followed by their resizing into different sizes, as per the market demand. Slab sizes in Karauli are of size 3X2 feet (called as farshi) done by mainly 2-3 people and 10X2 feet (called aschidi) done bymainly8-10 persons. The thickness of these slabs variesfrom5- 10 centimetres. Loading and unloading of chidi done by different workers.

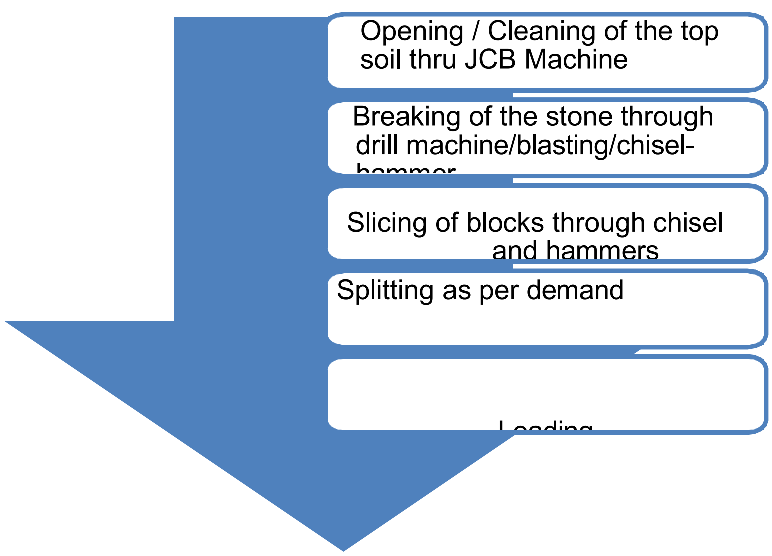

Figure 5:Mining Process

The mining of sandstone is mostly manual and labour-oriented occupation. The opencast quarrying requires loosening, loading and transporting, that depends on the shape, size, and depth of the pit, local topography and the required output (Madhavan and Sanjay, 2005).the topsoil. Then a blast is carried out to break up the sandstone. The beds of sandstone are split by driving holes using various shapes of chisels and hammers along bedding planes at an interval of 5-7 centimetres.

The general size of a quarry in Karauli is about 1-2 hectares. According to the Department of Mines and Geology of the Government of Rajasthan in the year 2013-14, there were about 140 quarries spread over 6,176 hectares in Karauli. The official estimates show that these quarries employ about 20,000 people. However, the worker employed could be much higher as the official figures do not include those involved in illegal quarrying. Most of the quarries are partnership companies, controlled by landlords or their family members. The local villagers also run few quarries at Karauli village with the actual license owner being the different person.

Figure 7: Photograph of tools used in mining

IV. TECHNIQUES AND PROCEDURES

OVERVIEW OF MIXED-METHODS APPROACH

The mixed-methods approach used in this study is an integration of both quantitative and qualitative research methodologies. This approach is increasingly recognized for its ability to provide a more nuanced understanding of complex research questions by combining the strengths of both methods. In the context of assessing soil contamination's impact on vegetation, the mixed-methods approach allows for the triangulation of data, ensuring that the findings are not only robust but also reflective of both measurable outcomes and contextual nuances.

The decision to employ a mixed-methods design stems from the need to capture the multifaceted nature of soil contamination and its effects on vegetation. While quantitative data provides objective measurements of contamination levels and their direct impact on plant health, qualitative data offers insights into how these changes affect biodiversity and the overall ecosystem. This combination allows for a more holistic understanding of the environmental challenges posed by mining activities in the region.

A. *Quantitative Research Methodology*

The quantitative aspect of the study involves the systematic measurement of heavy metal concentrations in soil and vegetation across the selected study sites. This method is critical for determining the extent of contamination and its potential impact on plant health. The quantitative data collection process is meticulously planned to ensure accuracy and reliability.

1. **Sampling Strategy**:

Soil and vegetation samples are collected from five locations near Red Sandstone mines (Bhauapura-Ratiapura, Kasara, Chobe ki Guwari, Mokanpura-Berda, Bhakari) and one control area Suroth (Karauli)). The selection of these sites is based on their proximity to mining activities, which is expected to result in a gradient of contamination levels. Each location is subdivided into multiple sampling points to capture spatial variability in contamination.

Soil samples are collected from different depths (0-15 cm, 15-30 cm) to assess the vertical distribution of contaminants. Vegetation samples include both roots and shoots to evaluate how contaminants are taken up and distributed within plants.

2. **Laboratory Analysis**:

The collected samples are analyzed in a laboratory to measure the concentrations of heavy metals such as lead (Pb), cadmium (Cd), arsenic (As), and mercury (Hg). These metals are selected based on their known association with mining activities and their potential to cause significant harm to vegetation and human health.

Advanced analytical techniques such as Atomic Absorption Spectroscopy (AAS) and Inductively Coupled Plasma Mass Spectrometry (ICP-MS) are employed to ensure precise and accurate measurements. The data generated from these analyses provide a quantitative baseline for assessing contamination levels across the study sites.

3. **Data Analysis**:

The quantitative data is subjected to statistical analysis to identify patterns and correlations between contamination levels and vegetation health. Descriptive statistics (mean, median, standard deviation) are calculated to summarize the data, while inferential statistics (ANOVA, regression analysis) are used to test hypotheses regarding the impact of contamination on plant growth and health.

Spatial analysis techniques, such as Geographic Information System (GIS) mapping, are utilized to visualize the distribution of contamination across the study area. This visualization helps in identifying hotspots of contamination and areas that may require remediation.

B. Qualitative Research Methodology

The qualitative component of the study focuses on understanding the broader ecological impacts of soil contamination on vegetation health and biodiversity. This aspect of the research is crucial for capturing the changes in ecosystem dynamics that may not be immediately evident through quantitative measurements.

1. **Field Observations**:

Detailed field observations are conducted at each study site to assess the health and vitality of vegetation. This includes documenting visible signs of stress in plants, such as leaf discoloration, stunted growth, and reduced biomass. The presence of these symptoms is compared across sites to determine the severity of contamination's impact.

Additionally, biodiversity assessments are carried out to evaluate the diversity and abundance of plant species in contaminated and control areas. These assessments help in identifying any shifts in species composition that may be attributed to soil contamination.

2. **Ecological Assessments**:

Ecological assessments are performed to evaluate the broader environmental consequences of soil contamination. This includes examining changes in soil microbial communities, which play a crucial role in nutrient cycling and plant health. Soil samples are analyzed for microbial diversity using molecular techniques such as DNA sequencing.

The findings from these assessments contribute to a deeper understanding of how soil contamination disrupts ecological processes and impacts long-term vegetation health.

C. Environmental and Ecological Characteristics

Each study site is characterized by distinct environmental and ecological conditions, which are documented to understand how these factors influence the impact of soil contamination on vegetation.

1. Climate:

The study area experiences a semi-arid climate with hot summers and mild winters. The region receives limited rainfall, which affects soil moisture levels and vegetation cover. These climatic conditions are important considerations when assessing the impact of soil contamination, as they influence the mobility of contaminants and the resilience of vegetation.

2. Soil Composition:

The soils in the study area are predominantly sandy loams with varying levels of organic matter. Soil samples from each site are analyzed to determine their physical and chemical properties, including pH, organic carbon content, and cation exchange capacity. These properties influence the retention and mobility of heavy metals in the soil, affecting their availability to plants.

3. Vegetation Types:

The vegetation in the study area consists of a mix of native and introduced species, including shrubs, grasses, and small trees. The diversity and abundance of vegetation are documented at each site to assess the impact of soil contamination on plant communities. Particular attention is given to the presence of indicator species, which are known to be sensitive to changes in soil conditions.

4. Hydrology

The hydrology of the study area plays a significant role in the distribution and concentration of contaminants, particularly heavy metals, in both soil and vegetation. Seasonal streams and intermittent water bodies, which are typical of the region, can act as conduits for the movement of contaminants from the mining sites to surrounding areas. During the monsoon season, increased water flow can lead to the leaching of contaminants from mine tailings and their subsequent deposition in downstream areas. These hydrological processes are critical in understanding the spatial patterns of contamination and their impact on vegetation.

At each study site, the hydrological conditions are carefully documented, including the presence of surface water, the flow direction of streams, and the proximity of water bodies to mining activities. This information is essential for identifying potential pathways of contaminant transport and areas where vegetation may be particularly vulnerable to contamination. Additionally, the water quality in these streams and water bodies is tested for heavy metal concentrations, which can provide further insights into the extent of contamination and its potential impact on aquatic and riparian vegetation.

D. Chemical Composition and Analysis Techniques for Heavy Metals in Soil Samples

Heavy metals in soil can exist in various chemical forms and compositions, affecting their mobility, toxicity, and bioavailability. Identifying both the concentration and chemical composition is crucial for risk assessment, remediation planning, and environmental monitoring. This document outlines key techniques used to analyze heavy metals in soil, their principles, procedures, and the forms in which heavy metals typically occur.

E. Common Chemical Forms of Heavy Metals in Soil

Heavy metals are found in various chemical compositions in soils, often bound with organic matter, oxides, carbonates, sulfides, and silicates. Common forms include:

- Lead (Pb): PbO, $PbCO_3$, PbS, $PbCl_2$
- Cadmium (Cd): $CdCO_3$, CdS, CdO
- Arsenic (As): As_2O_3, AsO_4^{3-} (as H_3AsO_4), AsS
- Chromium (Cr): Cr_2O_3 (Cr(III)), CrO_4^{2-} (Cr(VI))
- Mercury (Hg): $HgCl_2$, HgS, elemental Hg^0
- Zinc (Zn): $ZnCO_3$, ZnS, ZnO
- Copper (Cu): CuO, Cu_2O, $CuCO_3$
- Nickel (Ni): NiO, $Ni(OH)_2$, $NiCO_3$

Identifying the chemical composition of heavy metals in soil samples involves determining both the presence and concentration of specific metals, as well as their chemical forms (speciation) or compounds. Below is a detailed overview of methods used to identify the chemical composition of heavy metals in soil, building on the previously discussed analytical techniques but focusing on their application to chemical composition and speciation. The response is comprehensive yet concise, covering principles, procedures, and key details.

1. Atomic Absorption Spectroscopy (AAS)

Purpose: Quantifies total metal concentration in soil samples. Principle: Measures light absorption by metal atoms at specific wavelengths to determine concentration. Procedure for Chemical Composition:

Sample Preparation: Dry and sieve soil (<2 mm). Digest with acids (e.g., aqua regia or HNO_3) to extract total metals (EPA Method 3050B).

Analysis: Use flame or graphite furnace AAS to measure absorbance at metal-specific wavelengths (e.g., 283.3 nm for Pb).

Identification: Match absorbance to calibration standards for metals like Pb, Cd, Cu, Zn, Ni, Cr. Limitations for Speciation: AAS provides total metal content, not chemical forms. Sequential extraction (e.g., Tessier method) can be paired to infer speciation (e.g., carbonate-bound, oxide-bound). Details:

Detection Limits: 0.01–1 mg/L (flame); 0.1–10 µg/L (graphite furnace).

Equipment: PerkinElmer, Agilent AAS systems.

Applications: Total concentration of individual metals.

2. Inductively Coupled Plasma Mass Spectrometry (ICP-MS)

Purpose: Quantifies trace and ultra-trace metal concentrations; can be coupled with speciation techniques. Principle: Ionizes metals in plasma and separates them by mass-to-charge ratio. Procedure for Chemical Composition:

Sample Preparation: Digest soil with HNO_3 or aqua regia (EPA Method 3051A).

Analysis: Nebulize the sample into argon plasma, detect ions using a mass spectrometer.

Speciation: Couple with techniques like high-performance liquid chromatography (HPLC-ICP-MS) to separate and identify metal species (e.g., Cr(III) vs. Cr(VI), As(III) vs. As(V)).

Identification: Compare ion intensities to multi-element standards. Formulas:

Detection Limits: 0.01–1 μg/L.

Metals: As, Cd, Pb, Hg, Cr, Cu, Zn.

Interferences: Isobaric (e.g., $^{40}Ar^{35}Cl^{+}$ on $^{75}As^{+}$), mitigated by collision cells.

Equipment: Thermo Fisher iCAP, Agilent 7900.

Applications: Total metal content; speciation with HPLC or ion chromatography (IC).

3. Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES)

Purpose: Quantifies multiple metals simultaneously; suitable for higher concentrations. Principle: Measures light emitted by excited metal atoms in plasma. Procedure for Chemical Composition:

Sample Preparation: Acid digestion (similar to ICP-MS)

Analysis: Introduce sample into plasma, measure emission at characteristic wavelengths (e.g., 324.7 nm for Cu).

Speciation: Limited; can be paired with HPLC or IC for species separation.

Identification: Compare emission intensities to calibration curves. Formulas:

Concentration: C=Ik C = \frac{I}{k} C=kI, where I II is emission intensity, k kk is a calibration constant. Details:

Detection Limits: 0.1–10 μg/L.

Metals: Cu, Zn, Pb, Cd, Ni, Fe.

Interferences: Spectral overlaps, mitigated by background correction.

Equipment: PerkinElmer Optima, ThermoiCAP.

Applications: Total metal analysis; less common for speciation.

4. X-Ray Fluorescence (XRF)

Purpose: Rapid, non-destructive identification of metal composition. Principle: Excites atoms with X-rays, causing emission of characteristic fluorescent X-rays. Procedure for Chemical Composition:

Sample Preparation: Minimal; dry and sieve soil or analyze directly (portable XRF).

Analysis: Irradiate sample with X-rays, detect emitted fluorescence using a spectrometer.

Identification: Match fluorescence energies to elemental libraries (e.g., 10.5 keV for Pb Lα line). Limitations for Speciation: Provides elemental composition, not chemical forms. Details:

Detection Limits: 1–10 mg/kg.

Metals: Pb, As, Cu, Zn, Cr, Cd.

Interferences: Matrix effects (e.g., soil moisture), corrected by software.

Equipment: Handheld (Niton XL5, Bruker Tracer) or benchtop (Rigaku ZSX).

Applications: Field screening, total metal content.

5. Atomic Fluorescence Spectroscopy (AFS)

Purpose: Sensitive analysis for specific metals (e.g., Hg, As). Principle: Measures fluorescence emitted by excited metal atoms, often in vapor form. Procedure for Chemical Composition:

Sample Preparation: Digest soil (e.g., HNO_3 for Hg) or use cold vapor generation (for Hg).

Analysis: Excite atoms with a light source, measure fluorescence intensity.

Speciation: Can distinguish species like Hg^{2+} or methylmercury with hyphenated techniques (e.g., GC-AFS).

Identification: Compare fluorescence to standards. Formulas:

Concentration: C=Ifk C = \frac{I_f}{k} C=kIf, where If I_f If is fluorescence intensity. Details:

Detection Limits: 0.01–1 µg/L.

Metals: Hg, As, Se, Sb.

Equipment: PSA Millennium Merlin.

Applications: Specialized for volatile metals, speciation possible.

6. Neutron Activation Analysis (NAA)

Purpose: Non-destructive trace element analysis. Principle: Irradiates samples with neutrons, inducing radioactivity; emitted gamma rays identify elements. Procedure for Chemical Composition:

Sample Preparation: Minimal; dry and homogenize soil.

Analysis: Irradiate in a nuclear reactor, measure gamma rays with a high-purity germanium (HPGe) detector.

Identification: Match gamma-ray energies to elemental signatures (e.g., 559 keV for ^{76}As). Limitations for Speciation: Identifies elements, not chemical forms. Formulas:

Activity:

$$A=N\cdot\sigma\cdot\phi\cdot(1-e-\lambda t),$$

where N is the number of atoms, σ is cross-section, ϕ is neutron flux, λ is decay constant.

Details:

Detection Limits: 0.01–1 mg/kg.

Metals: Cr, Co, As, Sb, rare earths.

Equipment: Requires reactor, HPGe detector.

Applications: Research, trace analysis.

7. Electrochemical Methods (e.g., Anodic Stripping Voltammetry, ASV)

Purpose: Quantifies specific metals; limited speciation. Principle: Deposits metals onto an electrode, then strips them off, measuring current peaks. Procedure for Chemical Composition:

Sample Preparation: Acid digestion to extract metals.

Analysis: Deposit metals on a working electrode (e.g., mercury drop) at a negative potential, then apply a potential sweep to measure stripping currents.

Identification: Match peak potentials to metals (e.g., -0.4 V for Pb vs. Ag/AgCl). Formulas:

Concentration: C=IpS C = \frac{I_p}{S} C=SIp, where Ip I_p Ip is peak current, S SS is sensitivity. Details:

Detection Limits: 0.1–10 µg/L.

Metals: Pb, Cd, Cu, Zn.

Equipment: Metrohm Voltammetry systems.

Applications: Field and lab analysis, limited speciation.

8. Sequential Extraction for Speciation

Purpose: Determines chemical forms (speciation) of heavy metals (e.g., exchangeable, carbonate-bound, oxide-bound, organic-bound, residual). Principle: Uses a series of chemical reagents to selectively extract metals in different binding forms. Procedure:
Tessier Method (common example):

Step 1: Exchangeable (e.g., 1 M $MgCl_2$, pH 7).

Step 2: Carbonate-bound (e.g., 1 M NaOAc, pH 5).

Step 3: Fe-Mn oxide-bound (e.g., 0.04 M NH_2OH•HCl).

Step 4: Organic-bound (e.g., H_2O_2/HNO_3).

Step 5: Residual (aqua regia or HF digestion).

Analysis: Analyze each fraction using AAS, ICP-MS, or ICP-OES.

Identification: Quantify metals in each fraction to infer speciation. Details:

Applications: Assess bioavailability and mobility (e.g., exchangeable Cd is more bioavailable).

Limitations: Operationally defined, not absolute speciation; time-consuming.

Standards: Modified BCR (Community Bureau of Reference) method.

9. X-Ray Absorption Spectroscopy (XAS)

Purpose: Direct speciation of heavy metals in soil. Principle: Measures X-ray absorption to determine oxidation state and coordination environment (e.g., XANES for oxidation state, EXAFS for bonding). Procedure:

Sample Preparation: Minimal; analyze soil directly or as pressed pellets.

Analysis: Use a synchrotron X-ray source to scan absorption edges (e.g., As K-edge at 11.867 keV).

Identification: Compare spectra to reference compounds (e.g., Cr(III) vs. Cr(VI)). Details:

Detection Limits: 10–100 mg/kg.

Metals: As, Cr, Pb, Hg, Zn.

Equipment: Synchrotron facilities (e.g., NSLS-II, ESRF).

Applications: Direct speciation, research-focused.

Limitations: Requires synchrotron access, high cost.

Key Considerations

Total vs. Speciation Analysis:

Total metal content: AAS, ICP-MS, ICP-OES, XRF, NAA, AFS, ASV.

Speciation: Sequential extraction, HPLC-ICP-MS, GC-AFS, XAS.

Sample Preparation:

Total Analysis: Acid digestion (HNO_3, HCl, HF, or aqua regia) per EPA 3050B/3051A.

Speciation: Milder extractions or minimal preparation for XAS/XRF.

Quality Control: Use certified reference materials (e.g., NIST SRM 2710), blanks, and duplicates.

Interferences: Matrix effects (organic matter, clay), spectral overlaps, or isobaric interferences.

Regulatory Standards: EPA SW-846, ISO 11466 for extraction, ISO 18227 for analysis.

F. Metal Extraction Procedure from Collected Soil Samples

The metal extraction process aims to isolate heavy metals from soil samples for subsequent analysis. The procedure ensures that metals bound in the soil matrix are released into a solution, which can be quantified using spectroscopic methods.

Procedure:

1. **Sample Preparation:**

Air-dried soil samples were ground to pass through a 2 mm sieve. Approximately 1 gram of the sieved soil was used for the extraction process.

2. **Acid Digestion:**

The soil sample was placed in a Teflon digestion vessel. A mixture of concentrated nitric acid (HNO_2) and hydrochloric acid (HCl) in a ratio of 3:1 was added to the sample. This mixture, known as Aqua Regia, effectively dissolves most metals.

The digestion vessel was heated at 95°C for 2 hours to ensure complete digestion of the soil. The sample was then allowed to cool to room temperature.

3. **Filtration and Dilution:**

The digested sample was filtered using Whatman filter paper to remove any remaining solid particles. The filtrate, which contains the extracted metals, was collected.

The filtrate was then diluted with deionized water to a known volume (usually 50 or 100 mL) for analysis.

4. **Storage:**

The diluted extract was stored in clean polyethylene bottles at 4°C until analysis. This prevents any changes in the concentration of metals in the extract.

5. **Analysis:**

The metal content of the extract was analysed using Atomic Absorption Spectroscopy (AAS), which quantifies the concentration of specific metals based on their absorption spectra.

V. RESULTS AND DISCUSSION

Comparative assessment of soil samples from the Bhauapura-Ratiapura mining area shows that contamination levels are quite high near the quarrying and stone processing areas, and gradually decrease with distance from the mine source. Chemical and analytical techniques confirm that metals exist in different chemical forms, which affect their mobility and bioavailability in soil. The results also show that fine dust particles generated during mining and transport play a major role in the spread of pollutants, leading to the deposition of heavy metals on nearby farmland and vegetation.

Statistical analysis supports a link between heavy metal concentrations and reduced vegetation health, suggesting that long-term exposure to these pollutants disrupts plant physiological functions and alters soil microbial activity. The findings from the reviewed literature are consistent with the observed patterns and indicate similar environmental challenges in other sandstone mining areas in Rajasthan. The discussion emphasizes that sandstone mining contributes to the regional economy, but it poses a serious threat to the ecological balance if not properly managed. The study emphasizes the importance of adopting sustainable mining, implementing regular soil and vegetation monitoring and introducing rehabilitation measures such as phytoremediation and controlled mining. Overall, the results confirm that without environmental safeguards and sustainable management strategies, the long-term ecological integrity of Rajasthan's red sandstone mining areas will continue to deteriorate, affecting both soil productivity and biodiversity.

Table 1: Summary of Reviewed Findings on Soil Contamination and Vegetation Health in Red Sandstone Mine Areas of Rajasthan

Key Aspect	Findings Reported in Literature	Environmental / Ecological Implications	Reference Trends
Heavy Metal Contamination	Most studies report high concentrations of Pb, Cd, Cr, and Ni in soils around sandstone mining zones.	Persistent accumulation leads to long-term soil pollution and metal toxicity.	Reported across Karauli, Dholpur, and Bharatpur mining belts.
Soil Quality Degradation	Decline in organic matter, pH imbalance, and reduced microbial activity observed near mine areas.	Decrease in soil fertility and impaired nutrient cycling.	Commonly discussed in environmental and geochemical reviews.
Spatial	Contamination levels	Indicates localized	Supported by

Distribution of Pollutants	highest near quarries and stone-cutting sites; decrease with increasing distance.	pollution gradient and airborne metal dispersion.	spatial and GIS-based assessment studies.
Chemical Forms of Metals	Metals found in oxide, carbonate, and organic-bound states influencing mobility and bioavailability.	Enhanced potential for plant uptake and food-chain contamination.	Highlighted in soil chemistry and environmental toxicology literature.
Vegetation Health Effects	Visible plant stress symptoms such as chlorosis, stunted growth, and biomass reduction noted.	Heavy metals disrupt photosynthesis, respiration, and root functions.	Reported in ecological and botanical assessments.
Dust and Airborne Deposition	Quarrying activities identified as major sources of dust and fine particulate metal spread.	Contributes to secondary soil contamination and leaf surface deposition.	Documented in environmental pollution and air quality studies.
Biodiversity and Ecological Balance	Reduction in plant diversity and alteration of natural vegetation composition near mine areas.	Long-term disruption of local ecological equilibrium.	Consistently reported across multiple regional reviews.
Statistical and Correlation Analysis	Strong correlation between heavy metal concentration and vegetation decline	Establishes cause–effect relationship between mining activity and	Found in environmental and agricultural research

	confirmed in various studies.	ecosystem deterioration.	analyses.
Sustainable Mining and Rehabilitation	Literature emphasizes lack of reclamation and need for eco-friendly mining practices.	Adoption of phytoremediation, green belts, and soil restoration measures recommended.	Discussed in environmental management and policy studies.

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