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Tracing the Environmental Footprint of Abandoned Quarries: Hydro-Geochemical and Soil Quality Assessment in Kollam, India

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Abstract

Abandoned granite quarries are increasingly recognized as significant contributors to environmental degradation, especially in ecologically sensitive landscapes like Kollam District in Kerala, India. This study provides a comprehensive environmental assessment of three abandoned quarries namely Nadapara, Cherukara, and Vayyanam focusing on hydro-geochemical, water quality, soil quality, heavy metal contamination, spatial distribution patterns and biodiversity disruption. Quarry water samples revealed slightly alkaline pH, high phosphate levels, and total coliforms exceeding 900/100 mL, indicating microbial contamination and eutrophication risk. Soil analysis showed strong acidity, low organic carbon and high bulk density, suggesting severe compaction and nutrient loss. T-tests confirmed significant differences in organic carbon and moisture content across sites. Heavy metals like Fe, Pb, Cr, and Ni, were within global safety limits but exhibited contamination potential due to enhanced mobility in acidic, low-organic soils. Empirical variogram modelling revealed extensive lateral dispersion for Fe and Pb, while Ni and Cr showed localized retention. Correlation analyses highlighted strong negative associations between Fe and organic carbon and significant positive trends between Lead and phosphorus. Biodiversity surveys documented 51 plant species and 25 faunal taxa, indicating ecological resilience despite degradation. These findings underscore the urgent need for remediation through soil alterations, native vegetation restoration, and environmental monitoring to safeguard ecological and human health in quarry impacted regions.

Keywords: Abandoned quarries; Soil quality; Water quality; Heavy metals; Variogram; Ecological resilience

Introduction

Stone quarrying is a globally significant activity supplying essential construction materials such as granite, sand, and laterite. In India, particularly in ecologically fragile regions like Kerala, unregulated and intensive quarrying has emerged as a serious environmental concern. Traditionally, quarrying operations in Kerala were small scale and often lacked regulatory oversight (Singh, 2006). However, rapid urbanization and infrastructure expansion, including roads, seawalls, and high-rise buildings have driven a sharp increase in the scale and frequency of extraction activities (Alex and Sajeew, 2017).

Kerala now hosts over 3,000 quarry sites, many of which are operated illegally or seasonally without scientific planning or environmental management. These quarries have altered the geophysical landscape, causing extensive degradation of land, water and biodiversity (Prasannakumar et al., 2011). Notably, in Kollam District characterized by charnockite and gneissic lithology, abandoned quarries are increasingly becoming stagnant pits that disrupt groundwater regimes and act as sinks



for pollutants. The accumulation of residual explosives, dust and heavy metals poses threats to both aquatic ecosystems and public health (Lad and Samant, 2014; Ifeoma et al., 2014).

The adverse impacts of quarrying are multifaceted, including habitat destruction, topsoil erosion, deforestation, air and noise pollution and contamination of both surface and groundwater (Ekka and Behera, 2011). Quarry pits often breach the groundwater table, causing depletion through continuous pumping, while surface runoff from disturbed sites carries heavy metals such as Pb, Cr, and Ni, contributing to long-term soil and water contamination (Jarup, 2003; Ifeoma et al., 2014). Moreover, microbial contamination linked to stagnant quarry waters presents serious health hazards through the spread of waterborne diseases (WHO, 2011; Koshy and Nayar, 1999).

Kollam District serves as a critical example of the broader environmental consequences of unmanaged quarrying in the Western Ghats belt. With over 300 abandoned or active quarries, the region faces declining water quality, acidified soils, loss of biodiversity and heavy metal build up. While isolated studies have assessed some aspects of quarry impacts, an integrated evaluation encompassing water and soil chemistry, heavy metal distribution, spatial modelling, and biodiversity documentation remains limited. This study addresses this gap by evaluating the environmental footprint of three abandoned quarries in Kollam through hydro-geochemical analysis, soil quality assessment, spatial variogram modelling, and ecological surveys. The findings are intended to guide sustainable land management practices, inform ecological restoration efforts, and support public health interventions in quarry affected areas.

Methodology

Study area

This study was conducted at three abandoned granite quarries in Nadappara, Cherukara, and Vayyanam within Kottarakkara Taluk, Kollam District, Kerala (Fig.1). The sites, selected for their geological features and accessibility, are characterized by charnockite lithology, minimal vegetation and sparse human activity due to water scarcity. Primarily, all data were collected at a single time point likely during the dry or post-monsoon season, limiting insights into seasonal variations typical of Kerala's climate. At each quarry, two soil samples were collected from distinct points within each quarry to account for spatial heterogeneity, while a single composite water sample was collected from the central pit of each quarry.

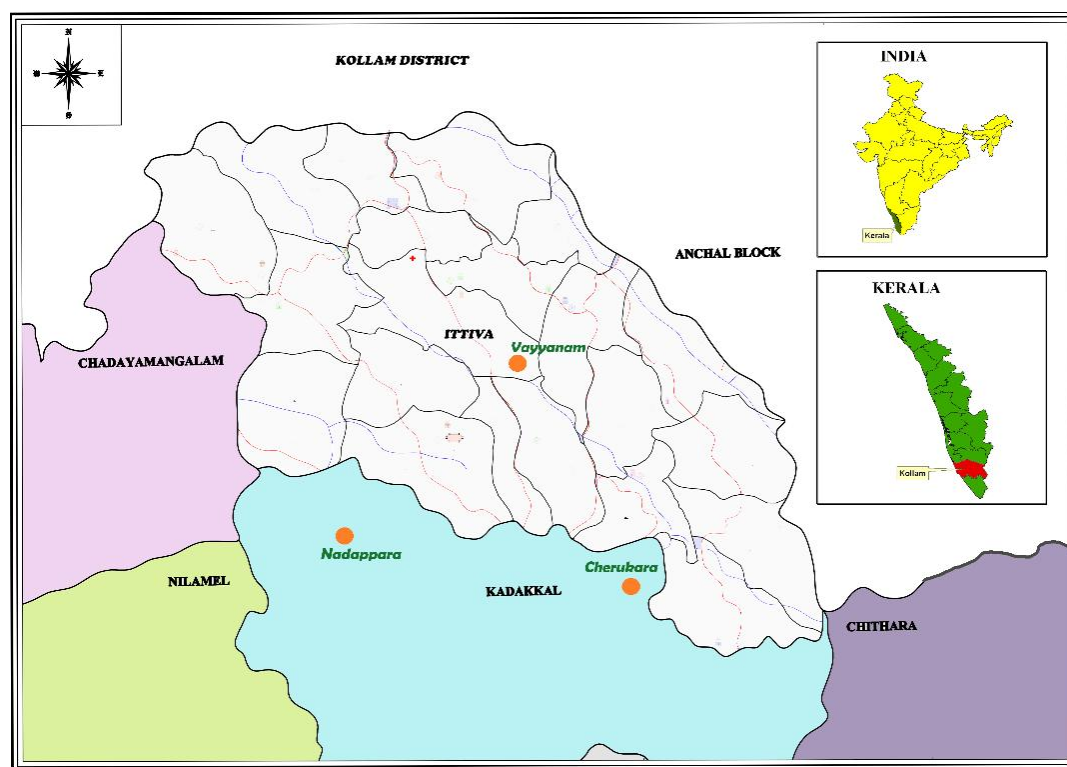


Fig. 1. Map showing the study locations

Water sample collection and analysis

One surface water sample from each quarry pits were collected in clean polythene bottles. Onsite measurements of pH and turbidity were taken immediately. Microbiological assessments, including total coliform estimation, were performed using sterile techniques and the Most Probable Number

(MPN) method. Laboratory analysis covered pH, electrical conductivity (EC), total dissolved solids (TDS), salinity, hardness, alkalinity, free CO₂, nitrate, phosphate, sulphate, and total coliforms using standard titrimetric, gravimetric, and spectrophotometric methods (APHA, 2017). All laboratory analysis including physicochemical parameters, microbial counts (MPN), and heavy metal quantification by AAS, were conducted in duplicate (n = 2) to ensure reproducibility.

Soil sample collection and Analysis

Soil samples (0 - 20 cm depth) were collected from multiple points at each site, air dried, sieved (2 mm), and stored for analysis. Parameters assessed included pH, EC, organic carbon, available nitrogen, phosphorus, potassium, bulk density, moisture content, and water holding capacity using standard soil testing protocols. Heavy metal contamination (Cr, Pb, Ni, Fe) was evaluated in duplicate (n = 2) through acid digestion and quantified using Atomic Absorption Spectroscopy (AAS) to ensure reproducibility. Empirical variogram analysis and Kriging-based contamination risk map for Lead concentration was conducted using ArcGIS (v10.x) with the Geostatistical Analyst extension to examine the spatial distribution and autocorrelation of heavy metals (Ni, Fe, Cr, Pb) in quarry soils. Semivariance values were calculated for each element at multiple lag distances, and variogram models were fitted using both spherical and exponential functions commonly employed in geostatistical modelling due to their ability to capture short and medium range spatial continuity (Isaaks and Srivastava, 1989).

Multivariate Statistical Analysis

To evaluate the significance of differences in soil parameters across quarry sites, independent two sample T-tests were performed for key physicochemical variables such as pH, organic carbon, nitrogen, phosphorus, potassium, bulk density, and moisture content. The tests were conducted using Microsoft Excel and statistical software, with significance set at $p < 0.05$. Correlation analysis was carried out using both Pearson's correlation coefficient (r) and Spearman's rank correlation coefficient (ρ) to assess linear and monotonic relationships, respectively, between soil nutrients and heavy metal concentrations (Ni, Fe, Cr, Pb). This dual approach provided robust insight into the underlying associations influenced by soil chemistry and metal mobility. Standard error (SE) was calculated for each measured parameter to quantify variability and ensure reliability of mean values. SE was computed using the formula $SE = \frac{SD}{\sqrt{n}}$, where SD is the standard deviation and n is the number of replicates per site.

Biological survey

A preliminary ecological survey was conducted through visual encounter methods to document flora and fauna around the quarry sites using standard references. Observations focused on vegetation types and faunal presence (amphibians, reptiles, insects) to assess habitat disturbance and potential ecological impacts of quarrying.

Results

Water Quality

The physicochemical analysis of quarry water revealed notable variation across the three sites, indicating differing degrees of water quality degradation (Table 1). Quarry 3 (QW₃) exhibited the highest levels of salinity, electrical conductivity, total dissolved solids, hardness, alkalinity, and phosphate, suggesting elevated mineral content and nutrient enrichment likely due to prolonged water stagnation and geological interactions. Total coliform count was also highest in QW₃, exceeding WHO standards and indicating microbial contamination. In contrast, Quarry 1 (QW₁) showed the lowest values for most parameters, reflecting relatively oligotrophic conditions but still recorded a high coliform load with 350/100 mL, possibly from human interactions. Quarry 2 (QW₂) presented intermediate values across parameters, serving as a transitional profile.

Soil Characteristics

The physicochemical analysis of quarry soils across six sampling sites revealed pronounced degradation in soil quality, with pH values ranging from 4.7 to 5.9, indicating moderately to strongly acidic conditions that can hinder nutrient availability and microbial activity. Organic carbon content was markedly low, particularly in Quarry 2 Site 2 (Q₂S₂) at 0.16%, reflecting severe organic matter depletion due to excavation and vegetation loss. Nitrogen levels remained moderately consistent, while phosphorus showed high spatial variability, ranging from 5.3 kg/ha in Q₃S₁ to 45 kg/ha in Q₃S₂. Potassium levels were relatively stable but reduced in disturbed sites. Low Bulk density values and moisture content indicated compacted soils with poor porosity and diminished water retention capacity (Table 2).

Table 1. physicochemical properties of quarry water

Sl. No	Parameters	Quarry 1 (QW ₁)	Quarry 2 (QW ₂)	Quarry 3 (QW ₃)	Standard error
1	pH	7.10	7.05	7.46	0.129
2	Electrical Conductivity (µs/cm)	86.91	179.2	218.4	38.975
3	Total dissolved solids (mg/L)	274.6	143.2	210.3	37.934
4	Salinity (mg/L)	68.4	80.26	217.9	47.978
5	Total Hardness (mg/L)	20	40	110	27.284
6	Alkalinity (mg/L)	30	40	80	15.275
7	Free Carbon dioxide (mg/L)	16	20	12	2.309
8	Nitrate (mg/L)	0.04	0.21	0.355	0.091
9	Phosphate (mg/L)	0.03	0.07	0.118	0.025
10	Sulphate (mg/L)	11.01	13.18	14.15	0.928
11	Total coliforms (/100ml)	350	27	900	254.837

Table 2. Physicochemical properties of quarry soil

Sl. No	Parameters	Quarry 1		Quarry 2		Quarry 3		Standard error
		Site 1	Site 2	Site 1	Site 2	Site 1	Site 2	
		(Q ₁ S ₁)	(Q ₁ S ₂)	(Q ₂ S ₁)	(Q ₂ S ₂)	(Q ₃ S ₁)	(Q ₃ S ₂)	
1	pH	5.9	5.2	4.9	5.1	4.7	5.1	0.166
2	Total Suspended Solids (mhos/cm)	0.07	0.13	0.09	0.10	0.17	0.11	0.014
3	Organic Carbon (%)	1.11	0.99	0.19	0.16	0.59	0.56	0.160
4	Nitrogen (%)	1.063	1.078	1.098	1.190	1.048	1.066	0.021
5	Phosphorus (kg/ha)	24.4	26.8	15.2	42	5.3	45	6.229
6	Potassium (kg/ha)	302.4	224	235.2	212.8	257.6	235.2	13.066
7	Bulk Density (g/cm ³)	1.63	1.72	1.56	1.5	1.79	1.84	0.054
8	Moisture Content (%)	2.9	2.1	4.68	4.77	10.1	9.86	1.406
9	Water Holding Capacity (%)	12.86	13.01	9.98	9.76	11.1	10.9	0.567

Heavy Metal Concentration

The heavy metal analysis of quarry soils revealed varying concentrations of nickel (Ni), iron (Fe), chromium (Cr), and lead (Pb) across the six sampling sites, indicating both geogenic influence and anthropogenic disturbance. Iron was the most abundant metal, with the highest concentration observed in Quarry 2 Site 1 (Q₂S₁) at 1263.25 mg/kg, suggesting significant mineral enrichment or residual impact from blasting activities. Lead concentrations ranged from 22.16 to 32.03 mg/kg, peaking in Q₂S₂, raising concern due to its persistence, toxicity, and potential mobility in acidic soils. Chromium levels were moderately high, with a maximum of 27.89 mg/kg in Q₁S₂, while nickel concentrations remained comparatively lower, ranging between 0.59 and 1.43 mg/kg (Table 3).

Table 3. Heavy metal analysis of quarry soil

Sl. No	Heavy Metal (mg/kg)	Quarry 1		Quarry 2		Quarry 3		Standard error
		Site 1	Site 2	Site 1	Site 2	Site 1	Site 2	
		(Q ₁ S ₁)	(Q ₁ S ₂)	(Q ₂ S ₁)	(Q ₂ S ₂)	(Q ₃ S ₁)	(Q ₃ S ₂)	
1	Nickel (Ni)	1.04	0.76	1.43	0.59	0.97	1.17	0.121
2	Iron (Fe)	886.56	931.82	1263.25	1223.29	1071.30	783.85	78.360
3	Chromium (Cr)	24.71	27.89	18.91	19.68	18.17	26.79	1.748
4	Lead (Pb)	25.59	28.59	24.43	32.03	22.16	27.02	1.403

Biodiversity

The biodiversity assessment conducted around the abandoned quarry sites in Kollam District revealed a resilient yet disturbed ecological framework, with a notable presence of both flora and fauna despite significant anthropogenic pressures. A total of 51 plant species were recorded, including *Careya arborea*, *Mangifera indica*, and *Acacia auriculiformis*, predominantly from families like Fabaceae and Euphorbiaceae, reflecting the adaptability of hardy, nitrogen fixing species in degraded, acidic soils. Uniform vegetation patterns across the sites suggest comparable regeneration potential, although limited by poor soil conditions and heavy metal contamination. Faunal diversity included six mammalian species such as *Bandicota bengalensis* and *Cynopterus sphinx*, several reptiles like *Calotes versicolor*, amphibians including *Duttaphrynus melanostictus*,

insectivorous birds, and pollinator butterflies, indicating the persistence of basic trophic interactions.

Discussion

Water quality and hydro-chemical trends

The water quality assessment across the three quarry sites revealed a slightly alkaline nature, well within the acceptable ranges prescribed by BIS and WHO standards. The alkalinity is likely linked to bicarbonates and carbonates released through mineral weathering, a common geochemical process in quarry-impacted environments. Electrical conductivity and total dissolved solids indicated moderate ionic enrichment, reflecting mineral dissolution from disturbed rock surfaces (APHA, 2017). Phosphate levels at one site slightly exceeded the WHO threshold, suggesting a risk of nutrient enrichment and potential eutrophication. Sulphate concentrations, while within safe limits, were consistent with dissolution from gypsum and sulphide bearing rocks processes often observed in quarry leachates (Jarup, 2003). Fig. 2 illustrate the physico chemical properties of Quarry water.

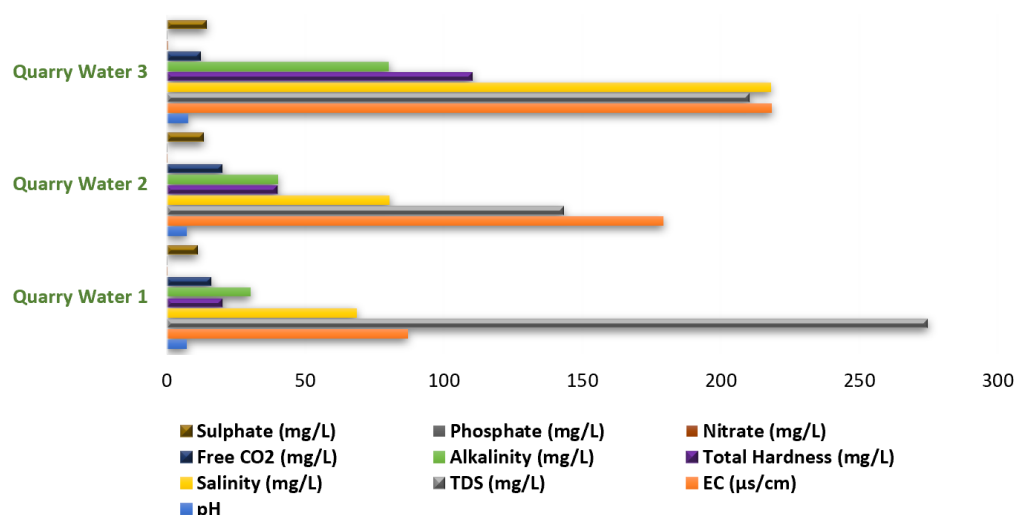


Fig. 2. Graph showing physico-chemical properties of Quarry water

Microbial analysis showed that all sites exceeded WHO's safe limit for coliforms, with one quarry exhibiting particularly high contamination levels. Such microbial pollution may be attributed to stagnant quarry waters receiving runoff and faunal inputs, a pattern previously reported in quarry-impacted ecosystems of Kerala (Koshy and Nayar, 1999; WHO, 2011). The comparative analysis of sites revealed that one quarry exhibited the highest mineralization and nutrient load, another showed oligotrophic conditions but still elevated coliforms, while the third displayed an intermediate profile. These gradient highlights differential ecological pressures across sites, with increasing risks of eutrophication and microbial contamination, underscoring the need for long-term monitoring and targeted management strategies (Carpenter et al., 1998).

Soil physicochemical degradation

The soils of the quarry sites exhibited moderately to strongly acidic conditions, typical of lateritic soils in tropical monsoon regions. Such acidity adversely influences nutrient availability and microbial functioning, thereby limiting soil fertility. Organic carbon levels were particularly depleted in sites subjected to intensive blasting and excavation. This pattern is consistent with earlier findings by Rani et al. (2017), who reported significant organic carbon losses in quarry-adjacent soils, largely due to vegetation removal and aerial dust deposition. Reduced nitrogen availability in these disturbed soils further reflects the disruption of microbial biomass and nutrient cycling, aligning with observations by Heal et al. (2017) that highlight the dependence of nitrogen dynamics on organic matter and microbial activity.

Phosphorus availability showed pronounced variability across sites, a trend attributable to differences in mineral weathering and vegetation cover. Similar site-specific fluctuations were noted by Rani et al. (2017), who linked phosphorus variation in quarry-affected soils to dust deposition and disrupted soil structure. In addition, the soils demonstrated high bulk density and low moisture retention, characteristic of compaction resulting from quarrying disturbances. Such compaction, often associated with organic carbon depletion, impairs porosity, reduces water-holding capacity, and ultimately diminishes soil fertility and resilience. Collectively, these findings

underscore how quarry operations alter soil chemistry and structure, producing conditions that constrain ecological recovery and land-use sustainability.

T-test Analysis

The t-test results for soil parameters across quarry sites compares each parameter between pairs of quarries (Q_1 vs Q_2 , Q_1 vs Q_3 , and Q_2 vs Q_3) to determine if the observed differences are statistically significant (Table 4). The results for soil parameters across quarry sites reveal significant differences in certain key variables, highlighting the heterogeneous impact of quarrying activities on soil quality. Most notably, organic carbon content showed a statistically significant difference between Quarry 1 and Quarry 2 ($p = 0.0332$), suggesting severe depletion of organic matter in Quarry 2, likely due to intense excavation and vegetation loss. A similar trend, though not statistically significant at the 0.05 level, was observed between Quarry 1 and Quarry 3 ($p = 0.0657$), reinforcing concerns about widespread organic degradation. Other parameters, such as soil pH, nitrogen, and moisture content, did not show significant differences ($p > 0.2$), indicating a relatively uniform impact across sites for these attributes. This analysis supports the hypothesis that quarry induced disturbances have uneven effects on soil properties, particularly with respect to organic matter depletion. Although the t-test indicated a significant difference in organic carbon, the ecological relevance of this difference should be considered alongside statistical outcomes, since organic matter is highly sensitive to site disturbance and directly influences nutrient cycling and microbial activity (Heal et al., 2017). Effect size metrics, in addition to p-values, will be valuable in future studies to better contextualize these differences.

Table 4. T-test results for soil parameters across quarry sites.

Parameter	Comparison	t-statistic	p-value
pH	Q_1 vs Q_2	1.511	0.3468
	Q_1 vs Q_3	1.612	0.2785
	Q_2 vs Q_3	0.447	0.7117
Organic Carbon	Q_1 vs Q_2	14.148	0.0332
	Q_1 vs Q_3	7.68	0.0657
	Q_2 vs Q_3	-18.856	0.0028
Nitrogen	Q_1 vs Q_2	-1.577	0.3506
	Q_1 vs Q_3	1.152	0.3716
	Q_2 vs Q_3	1.856	0.3009
Phosphorus	Q_1 vs Q_2	-0.223	0.8599
	Q_1 vs Q_3	0.023	0.9856
	Q_2 vs Q_3	0.144	0.9003
Potassium	Q_1 vs Q_2	0.962	0.4939
	Q_1 vs Q_3	0.412	0.7434
	Q_2 vs Q_3	-1.414	0.2929
Bulk Density	Q_1 vs Q_2	2.681	0.1333
	Q_1 vs Q_3	-2.72	0.1459
	Q_2 vs Q_3	-7.298	0.0199
Moisture Content	Q_1 vs Q_2	-5.528	0.1096
	Q_1 vs Q_3	-17.911	0.0222
	Q_2 vs Q_3	-41.003	0.006

Heavy metals and contamination

Quarry soils contained measurable levels of chromium, lead, nickel, and iron, generally within global agricultural limits yet still posing contamination risks linked to quarrying activities. Elevated chromium and lead near blasting zones highlight localized anthropogenic influence, with lead being particularly concerning due to its toxicity, impact on plant growth, and potential to cause enzymatic disruption and neurological disorders under chronic exposure (WHO, 2011). Nickel and iron, though largely geogenic from charnockite bedrock, also present ecological risks since excessive nickel can inhibit root elongation and high iron restricts phosphorus availability in acidic soils (Ifeoma et al., 2014). Spatial analysis indicated iron as the most abundant, while lead and chromium showed moderate but significant accumulation capable of disrupting microbial activity and nutrient cycling (Jarup, 2003). Overall, localized enrichment suggests both natural and anthropogenic sources, underscoring the need for detailed spatial sampling and health risk assessments.

Variogram modelling and spatial analysis

The variogram analysis of heavy metal concentrations in quarry soils revealed distinct spatial behaviours between the elements (Table 5). Lead (Pb) and Iron (Fe) exhibited strong spatial autocorrelation, with high sill values (0.15 - 0.18) and wide ranges (280 - 300 meters), indicating their potential for extensive lateral dispersion due to processes such as surface runoff and leaching from mineral-rich zones. These elements also showed strong model fits ($R^2 > 0.9$), reinforcing the

reliability of the spatial predictions. In contrast, Nickel (Ni) and Chromium (Cr) displayed weaker spatial structures, characterized by lower sill values and shorter ranges (<120 meters), suggesting more localized and patchy distributions likely influenced by limited mobility in the acidic quarry soils. The relatively low nugget effects for Ni and Cr indicate minimal random variation or measurement error, while the moderate nugget values for Pb and Fe reflect small scale heterogeneity or sampling variation. Overall, the variogram parameters highlight that Pb and Fe pose broader environmental risks due to their greater dispersion potential, necessitating targeted monitoring and remediation in high exposure zones. (Fig. 3).

Table 5. variogram analysis with key geostatistical parameters

No.	Heavy Metal	Nugget (C_0)	Sill ($C_0 + C$)	Range (m)	Model Type	R^2 (Model Fit)
1	Nickel	Low (0.01)	Moderate (0.04)	Short (<100 m)	Exponential	0.72
2	Iron	Moderate (0.05)	High (0.18)	Wide (300 m)	Spherical	0.89
3	Chromium	Low (0.03)	Moderate (0.08)	Short to moderate (120 m)	Exponential	0.76
4	Lead	Moderate (0.04)	High (0.15)	Wide (280 m)	Spherical	0.91

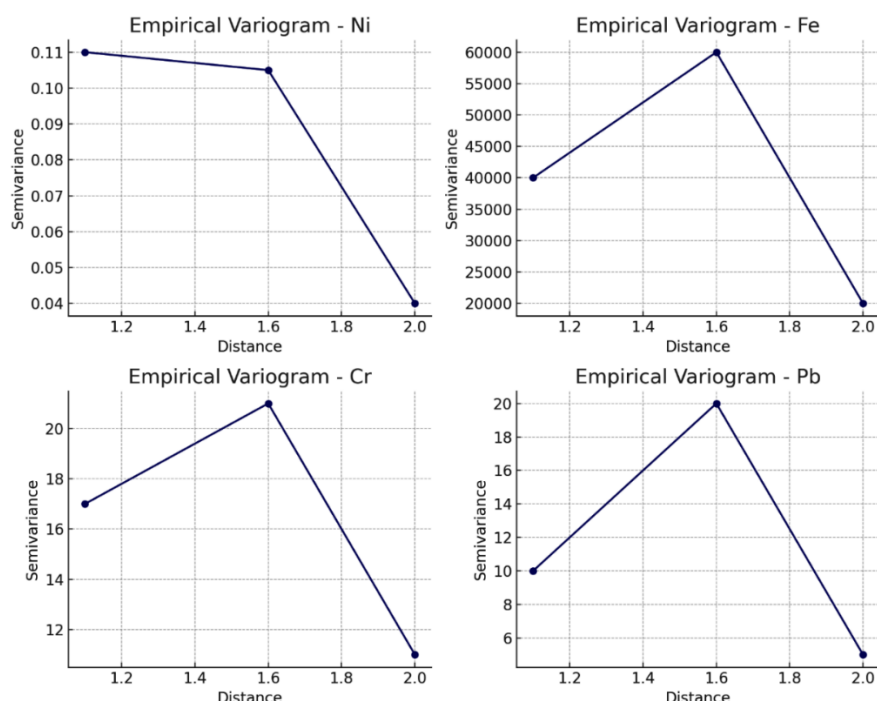


Fig. 3. Empirical Variograms for the heavy metals (Ni, Fe, Cr, Pb) in the soil

GIS-based contamination risk analysis

The Kriging-based contamination risk map for lead (Pb) highlights spatial variability in Pb concentrations across the three quarry sites (Fig. 4). Elevated Pb levels were interpolated around Nadapara and Cherukara, consistent with site-specific measurements reaching up to 32.03 mg/kg. Although these values remain within the general USEPA/BIS soil limits, they exceed the WHO guideline for agricultural soils (10 mg/kg), indicating localized risk especially under acidic soil conditions that enhance lead mobility. The map provides a visual representation of potential risk zones and underscores the importance of spatial modelling in identifying contamination hotspots. These insights are essential for guiding remediation priorities and protecting ecological and human health in quarry impacted areas.

Correlation matrix and analysis

The correlation matrix (Table 6) provides a comparative evaluation of relationships between soil physicochemical parameters and heavy metal concentrations (Ni, Fe, Cr, Pb) using both Pearson's r and Spearman's ρ , along with their respective significance levels (p -values). Several notable associations were observed, such as a positive Spearman correlation between potassium and nickel, and a moderate Pearson correlation between nitrogen and iron. Although these did not reach statistical significance ($p > 0.05$), likely due to the small sample size ($n = 6$), they reveal meaningful ecological trends. A strong negative Pearson correlation between organic carbon and iron ($r = -0.748$) and a similar trend with lead ($r = -0.179$) support the inference that reduced organic matter, commonly found in disturbed quarry soils enhances metal retention and mobility, substantiating findings by Rani et al. (2017) and Jarup (2003), who reported similar patterns of heavy metal enrichment under depleted organic conditions.

Furthermore, soil pH exhibited consistently negative, though weak to moderate, correlations with heavy metals such as chromium ($p = -0.537$) and lead ($p = -0.551$), affirming the established role of soil acidity in enhancing metal solubility and bioavailability in tropical lateritic soils (Jarup, 2003). These findings align with the broader narrative of metal mobility in acidic, compacted soils as documented in other quarry-impacted zones (Ifeoma et al., 2014). While these correlations offer valuable insights into underlying geochemical interactions, their statistical inconclusiveness underscores the need for increased sampling density and long-term monitoring to verify and model such relationships with confidence.

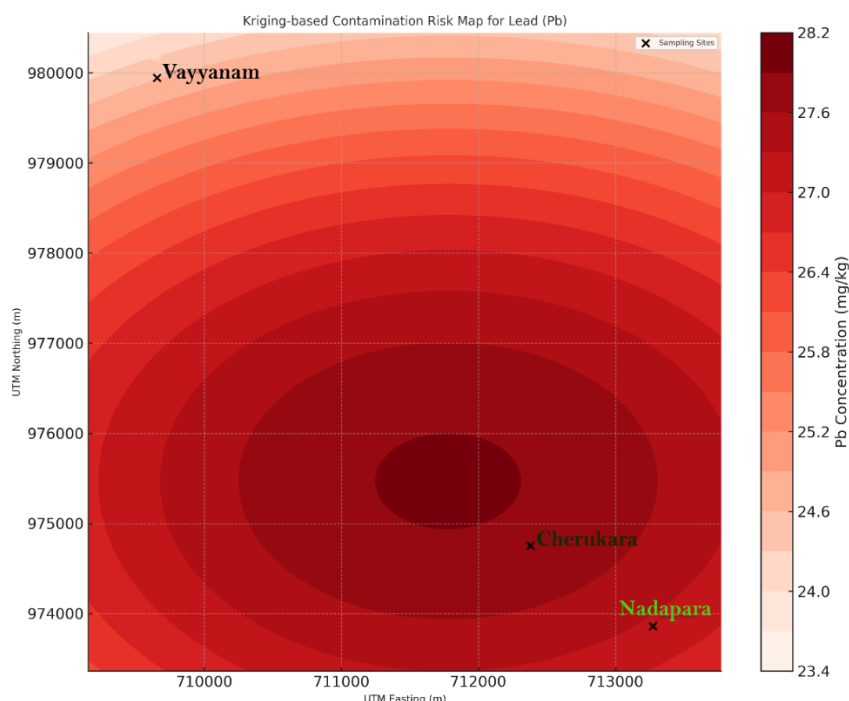


Fig. 4. Kriging-based contamination risk map for Lead (Pb) concentration across the three quarry sites.

Table 6. Quantitative Correlation table showing soil nutrients and heavy metals

Metal	Soil Parameters	Pearson r	Pearson p value	Spearman ρ	Spearman p value
Ni	pH	-0.105	0.8425	-0.203	0.6998
	Organic Carbon	-0.129	0.8073	0.029	0.9572
	Nitrogen	-0.504	0.3085	-0.2	0.704
	Phosphorus	-0.335	0.5166	-0.2	0.704
	Potassium	0.3	0.5638	0.522	0.2883
	Bulk Density	0.173	0.7426	0.257	0.6228
	Moisture Content	0.248	0.6353	0.086	0.8717
Fe	pH	-0.476	0.3397	-0.551	0.2574
	Organic Carbon	-0.748	0.0873	-0.6	0.208
	Nitrogen	0.615	0.1935	0.543	0.2657
	Phosphorus	-0.328	0.5261	-0.486	0.3287
	Potassium	-0.383	0.4539	-0.348	0.4993
	Bulk Density	-0.741	0.092	-0.714	0.1108
	Moisture Content	-0.152	0.7731	0.029	0.9572
Cr	pH	0.537	0.2719	0.783	0.0657
	Organic Carbon	0.689	0.1298	0.371	0.4685
	Nitrogen	-0.323	0.5319	0.143	0.7872
	Phosphorus	0.505	0.3067	0.714	0.1108
	Potassium	0.064	0.9047	-0.29	0.5774
	Bulk Density	0.443	0.3788	0.257	0.6228
	Moisture Content	-0.279	0.593	-0.6	0.208
Pb	pH	0.226	0.6662	0.551	0.2574
	Organic Carbon	-0.179	0.7345	-0.257	0.6228
	Nitrogen	0.797	0.0579	0.657	0.1562
	Phosphorus	0.814	0.0489	0.829	0.0416
	Potassium	-0.57	0.238	-0.783	0.0657
	Bulk Density	-0.441	0.3817	-0.314	0.5441
	Moisture Content	-0.422	0.4049	-0.371	0.4685

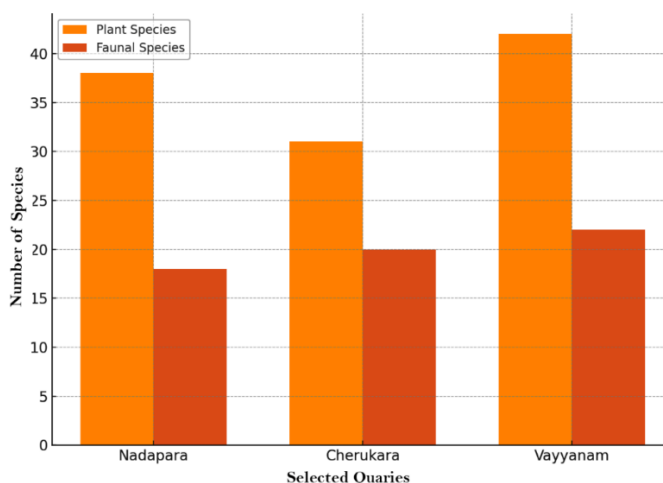


Fig. 5. Bar graph showing variation in plant species richness across the quarry sites

Biodiversity Interruption

The biodiversity assessment within a 10 km radius of the quarry sites revealed notable ecological richness despite anthropogenic pressures. Over 50 plant species, primarily from hardy families such as Fabaceae and Euphorbiaceae, were documented, indicating secondary succession and adaptation to acidic, nutrient depleted soils. Faunal observations included a diverse array of generalist species 6 mammals, 5 reptiles, 5 amphibians, 5 birds, and 5 butterflies, reflecting the persistence of essential ecological functions such as pollination and predation. Although no rare or endemic species were found, the continued presence of both flora and fauna suggests ecological resilience and recovery potential. These findings emphasize the importance of targeted restoration using native vegetation and habitat enrichment to rehabilitate the disturbed sites and promote long term ecosystem stability. The bar graph (fig. 5) illustrates the biodiversity across three quarry sites, Nadapara, Cherukara, and Vayyanam by comparing the number of recorded plant and faunal species. Vayyanam exhibited the highest plant diversity (42 species), while Nadapara had the richest faunal presence (18 species). Cherukara showed relatively balanced, though lower, richness in both categories. The visual comparison highlights site-specific variations in ecological resilience, with Vayyanam emerging as the most botanically diverse site.

Conclusion

The integrated assessment of abandoned quarry sites revealed that quarrying activities have significantly altered both soil and water quality, leading to soil acidification, compaction, organic matter depletion and disrupted nutrient dynamics, which collectively reduce fertility and ecological resilience. Although heavy metal concentrations largely remained within permissible global limits, localized enrichment was evident due to combined geological and anthropogenic influences, while microbial contamination in stagnant quarry waters posed potential health risks. Despite these impacts, the persistence of hardy plant species and generalist fauna indicates residual ecological resilience and potential for natural regeneration. The study underscores the urgent need for proactive management through ecological restoration with native species, restricted human access, and bioremediation measures, supported by continuous seasonal monitoring of soil and water quality. The integration of geostatistical analysis, biodiversity assessment and regulatory benchmarking offers a sustainable framework for quarry rehabilitation, long-term environmental monitoring and the protection of ecosystem as well as community health.

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Author Contributions

ASR led concept formation; conducted field investigation; curated data; performed laboratory analyses; carried out formal data analysis; drafted the original manuscript; and prepared visualizations and figures. AT supervised the project, enhanced the methodology, reviewed and edited the manuscript, validated the results, and approved the final version.

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Availability of data and materials

The data that support the findings of this study are available from the corresponding author upon reasonable request. Due to the nature of the field-based environmental data, including site-specific coordinates and ecological assessments, the dataset is not publicly archived to ensure ecological site protection and participant privacy during biodiversity documentation.

Competing interest

The authors declare no competing interests.

Ethics approval

Not applicable.



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