

Anthropogenic Hazards Assessment of Mining Activities in Surghar Range, Punjab, Pakistan

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Abstract

This study investigates the environmental impacts of coal mining in the Surghar Range, Punjab, Pakistan, with a focus on the contamination of soil and groundwater by potentially toxic elements (PTEs). To evaluate the extent and sources of contamination, 22 soil and 134 water samples were collected and analyzed using standard physicochemical and geochemical methods. This study identified iron (Fe), zinc (Zn), and lead (Pb) as the primary anthropogenic PTEs, while chromium (Cr) and arsenic (As) also appear at elevated levels in some locations. Soil PTE concentrations followed the order: Fe > Zn > Pb > Cr > As. Pollution indices revealed moderate to high levels of contamination, with a pollution load index (PLI) of 1.20 indicating overall moderate pollution. Although the potential ecological risk index (PERI) was relatively low at 18, the concentration levels of certain PTEs exceed internationally recognized thresholds, necessitating environmental remediation. Principal Component Analysis (PCA) identified Fe and Zn as dominant contributors to pollution. Groundwater analysis showed a spatial gradient in water quality: samples near the Indus River were of freshwater quality, while salinity levels increased westward toward the mining zone, with brine-level salinity detected in Tehsil Isa Khel. Water near mining areas exhibited lower pH and higher electrical conductivity (EC), indicative of acid mine drainage and sulfur-rich coal influence. Comparative analysis with global mining regions revealed that mean PTE concentrations in the Surghar Range are significantly higher, emphasizing the need for sustainable mining practices and targeted environmental management strategies to protect soil and water resources.

Keywords:

coal mining, environmental hazards, Potentially Toxic Elements (PTEs), water quality, soil contamination

1. Introduction

Coal remains a vital energy source, accounting for approximately 29% of global energy production, 41% of the world's electricity generation, and serving as a critical input for 44% of global industrial production (Wu and Chen, 2018). Both subsurface and open-pit coal mining operations involve a phased development in mine construction and the disposal of adjacent rocks, which often contain low content and iron sulfide minerals (Acharya and Kharel, 2020). These activities expose various rock types to atmospheric conditions and accelerate subsurface weathering processes. Consequently, acid mine drainage

can arise during and continue long after coal mining operations as a result of the oxidation of pyrite and other sulphide minerals exposed to air and water, and subsequent leaching of acidic oxidation products. Oxidation and hydrolysis processes and thus the formation of acid mine drainage is accelerated at low pH values of mine water, which enhances mineral dissolution and the release of toxic elements (Acharya and Kharel, 2020). The water quality degradation, irrigation water degradation, biodiversity and soil quality issues are the impacts of mining activities which directly impact agricultural productivity and human health (Tiwary, 2001; Mossa and James, 2013; Mensah et al., 2015).

Mining activities are recognized for introducing substantial levels of heavy metals into agricultural soils, resulting in the degradation of soil fertility, reduction in biodiversity and loss of crop productivity. For example, Mileusnić et al. (2014) assessed contamination from

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improperly disposed tailings at the Kombat mine in Namibia, revealing a significant accumulation of toxic metals that pose serious risks to soil health. Studies show that mining residues, through leaching, contribute to soil acidification and mobilization of metals, which further compromise soil quality and may have adverse impacts on surrounding ecosystems and human health (Koptsik, 2014; Zhang et al., 2015). Furthermore, the physical disturbances from mining operations lead to soil compaction, reduced permeability and a decline in organic matter, each of which diminishes the agricultural productivity of affected soils (Tordoff et al., 2000; Zhao et al., 2007).

Mining anthropogenic effects have always been serious concern for the ecological resources of the leased area. The consequences of mining activities affect almost every segment of the environment (Mossa and James, 2013) (see Figure 1). In South Africa, extensive gold mining operations have led to the release of toxic metals into surrounding environments, affecting both ecosystems and human health (Ochieng et al., 2010). Similarly, the coal mining regions in Appalachia, USA, have experienced severe water contamination due to acid mine drainage, resulting in elevated levels of heavy metals such as iron and aluminium (Palmer et al., 2010). In Australia, bauxite mining in the Darling Range has led to soil erosion and loss of biodiversity, posing long-term ecological challenges. In all these regions, to validate the findings, the concentrations of PTEs were compared with WHO drinking water quality standards, following the approach used in earlier studies (Ochieng et al., 2010; Palmer et al., 2010). Therefore, mining activities worldwide have led to significant environmental degradation, with detrimental effects on biodiversity, air, soil and water quality.

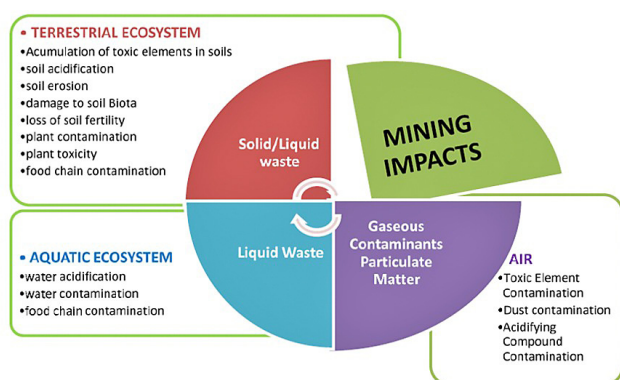


Figure 1. Potential environmental impacts of the mining industry (modified after Khan et al., 2020)

The Surghar Range, part of the Trans-Indus region of Pakistan, is geologically diverse, hosting significant mineral resources including coal in Paleocene–Eocene strata, iron ore in Cretaceous formations, and silica sand in Jurassic rocks. In the study area, coal is primarily extracted from the Hangu Formation (Paleocene), while

silica sand is mined from the Datta Formation (Jurassic). The Makarwal region, in particular, has a long history of coal mining, with approximately 140 active and abandoned mines. However, these operations have evolved with minimal adherence to modern environmental regulations and virtually no post-mining land reclamation, leading to severe degradation of local ecosystems. Despite the economic importance of these environmental resources, previous investigations in the area have focused predominantly on stratigraphy, lithology and resource assessments (Khan, 1949; Fatmi, 1972; Faruqi, 1983; Danilchik and Shah, 1987; Warwick and Javed, 1990; Shah, 2009; Umair et al., 2022), with little attention given to environmental consequences.

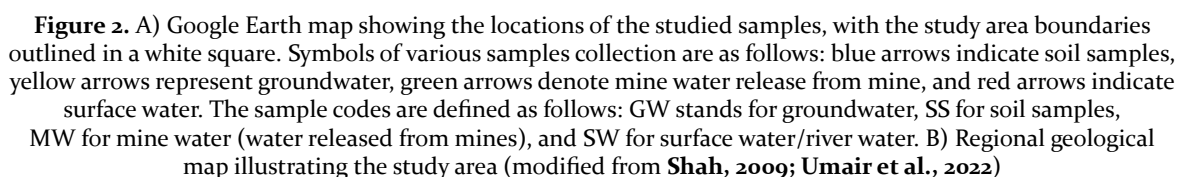
Over the past several decades, extensive coal and silica sand mining in the Surghar Range has proceeded largely unchecked, contributing to soil degradation, groundwater contamination, and loss of biodiversity. Despite clear evidence of ecological damage, there remains a critical gap in scientific literature that systematically examines the environmental implications of mining activities in this region. While numerous global studies have assessed the environmental impacts of mining, the localized effects within this geologically and ecologically sensitive region of Pakistan remain poorly understood. Most prior studies have focused solely on geological mapping or resource quantification, leaving the ecological and hydrochemical dimensions of mining-related degradation underexplored.

This study fills that gap by conducting the first thorough evaluation of the spatial distribution, concentration and ecological risk of potentially toxic elements (PTEs) in both soil and groundwater over the Surghar Range. This study uses an integrated methodological framework that includes in-situ field sampling, laboratory studies, multivariate statistical approaches and geographic modelling to provide a quantitative assessment of environmental deterioration. Key developments include the use of pollution indices and hydrochemical signatures to document acid mine drainage and heavy metal contamination, as well as a regional comparison of PTE concentrations and global mining standards to contextualize the data.

This work fills an essential scientific need by providing actual findings from a poorly controlled mining zone, while also establishing baseline environmental data for the region. The findings emphasize the importance of early policy interventions, land restoration measures, and the adoption of sustainable mining techniques. More broadly, the study provides a transferable analytical framework for other developing countries experiencing similar environmental hazards from mining activity.

2. Tectono-geological context

The Western Himalayas of Pakistan reveal a complex geological history shaped by the collision of the Indian and Eurasian plates, which initiated the Himalayan



The study area, part of the Surghar Range southwest of Islamabad (see **Figure 2**), marks the easternmost extension of the sub-Himalayan fold-and-thrust belt (**Khattak et al., 2017**), separated from the western Salt Range by the Kalabagh fault (**DiPietro and Pogue, 2004**). The Surghar Range displays a stratigraphic sequence of sedimentary rocks from the Triassic to recent periods, oriented east-west and dipping northward (**Shah, 2009**) (see **Figure 3**). The stratigraphy includes

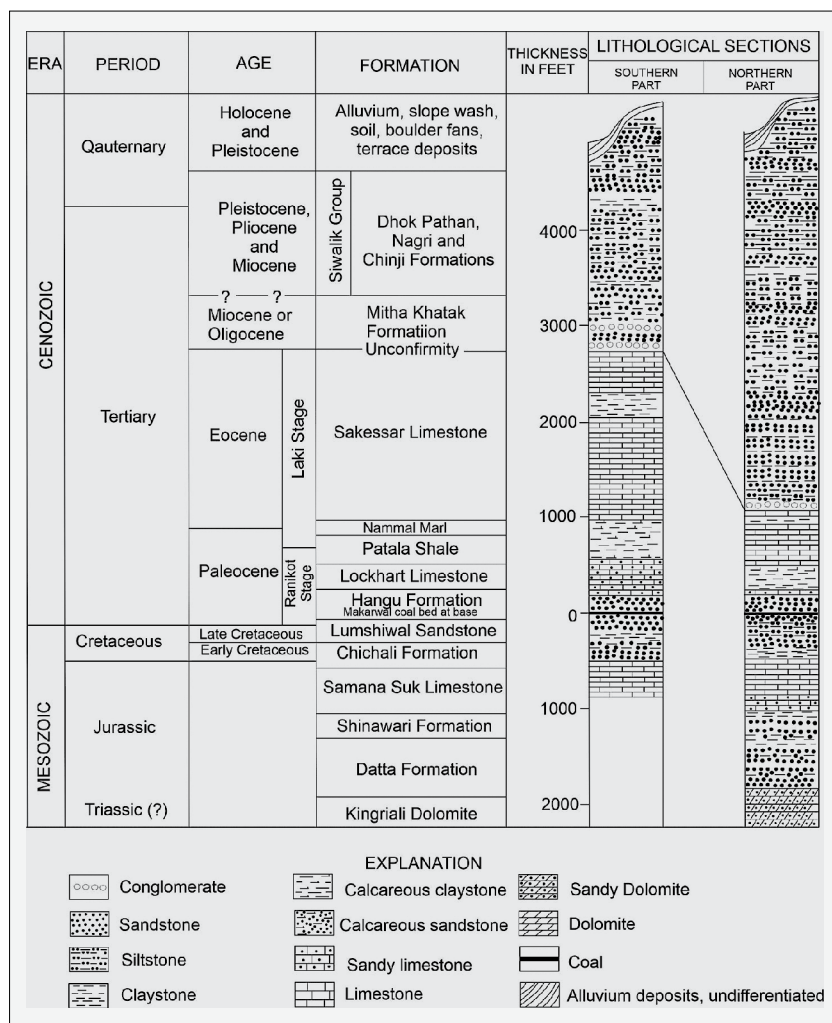


Figure 3. Stratigraphy of the study area and surrounding (modified after **Fatmi, 1972; Shah, 2009**)

formations from the Triassic Mianwali to the Eocene Sakessar Limestone, with notable formations like the Jurassic Datta (sandstone, shale, ferruginous silica sands) and Cretaceous Lumshiwal (iron-stained, coal-bearing sandstone) (**Shah, 2009**).

Mining of coal, silica sand and other resources in the Surghar Range, Punjab, Pakistan, has resulted in significant environmental impacts, particularly affecting soil quality, surface water and groundwater, raising concerns about the sustainability of these activities. Studies have shown that coal mining in the nearby Makarwal and Cherat areas has led to elevated concentrations of toxic trace elements in soil, exceeding safe thresholds (**Shah et al., 2019; Ali et al., 2023**). Similarly, groundwater contamination caused by the leaching of heavy metals from coal deposits has been reported, impacting water quality and posing health risks. While **Malkani (2017)** identified extensive silica sand deposits in the Mianwali District, including the Surghar Range, studies on the environmental consequences of silica sand extraction remain limited. This research addresses these gaps by assessing the combined impacts of coal and silica sand mining on soil, surface water and groundwater through field sampling, laboratory analysis and geospatial techniques.

3. Methodology

The area is part of the Surghar Range and is situated southwest of Islamabad. The study area, where extensive mining of coal, salt, silica sand and iron ore take place, was systematically divided for investigation into multiple grids, each covering a 3-square-kilometer area (see **Figure 2**). A systematic sampling approach was employed to collect soil and water samples from the study area to assess environmental impacts associated with mining activities. Specifically, 22 soil samples were extracted from designated tailing (dumping) sites at an approximate depth of 30.48 cm (1 foot) to analyze the potential contamination and alteration in soil properties due to disposal practices. Furthermore, a total of 134 water samples, representing both surface water (5 samples), mine related water sources (6 samples) and groundwater sources (123 samples), were collected across various strategically selected locations to evaluate the spatial distribution of potential pollutants and ascertain their impact on local water quality. This comprehensive sampling approach was designed to provide a robust dataset for environmental impact assessment and to support subsequent data analysis on contamination levels.

and patterns. In the study, river (surface water) samples were collected from various points along the river, especially near mining sites, using clean containers submerged at different depths to ensure representative sampling. Groundwater samples were taken from wells or boreholes, using clean sampling devices to extract water from different depths. These methods allowed for a comprehensive analysis of contamination levels and their distribution in both surface and groundwater sources across the study area.

The analysis of potentially toxic elements (PTEs), including Pb, Zn, Cr, Fe and As, was conducted at the Geosciences Advanced Research Laboratory in Islamabad, Pakistan, using inductively coupled plasma mass spectrometry (ICP-MS; PerkinElmer ELAN 6100). To prepare the soil samples for analysis, a multi-acid digestion was performed using a combination of nitric acid (HNO_3) and hydrochloric acid (HCl) in a closed-vessel microwave-assisted digestion system. This method effectively extracts trace elements from complex soil matrices, enabling the accurate detection of low-concentration PTEs. Rigorous quality control protocols were followed to ensure analytical accuracy and reliability. Certified reference materials (CRMs) were used to validate the accuracy of results, while method blanks and duplicate samples were included to assess precision. Additionally, regular calibration of the ICP-MS instrument and the use of control charts ensured consistent performance throughout the analytical process. The analysis procedure involved digesting 250 mg of calcinated powdered samples with a standard multi-acid solution to produce 25 cc of a 2M HCl solution with a 1:100 dilution for subsequent analysis using ICP-MS (HORIBA Jobin-Yvon Activa). This approach enabled the identification of PTEs contents within the same solution. The method provided a relative uncertainty of approximately 5% for the most sensitive elements and about 10% for others, with detection limits ranging from 5 to 20 ppb (equivalent to 0.5–2 ppm based on the dilution factor).

Regarding water quality analysis, several physico-chemical parameters were evaluated to characterize the sample profiles, such as pH, electrical conductivity (EC), total dissolved solids (TDS), calcium and magnesium concentrations, hardness and alkalinity. In-situ measurements of pH, electrical conductivity (EC), total dissolved solids (TDS) and temperature were conducted using portable meters. pH was measured using a calibrated pH meter (model pH-08107 of HANNA) by immersing the probe in each sample to ensure precise assessment of hydrogen ion concentration, reflecting the acidity or alkalinity of the water. The TDS were quantified with a TDS meter (model TDS Low of ECO Testr), providing a measure of the ionic content, which is crucial for assessing salinity and water purity. The EC was determined with a conductivity meter (model CM-1k of COND Meter), which measures the ability of water to conduct electricity, an indicator directly related to the

total ionic strength and salinity levels. Calcium and magnesium analysis was performed by complexometric titration with EDTA (ethylene diamine tetra-acetic acid), using specific indicators to ascertain the endpoint for each ion separately, which allowed for accurate individual quantification. Total hardness as CaCO_3 was determined also by titrating the sample with EDTA and calculating based on the required titrant volume to reach the endpoint, indicative of the water's scaling potential and its suitability for various uses. Sulphate concentrations were determined using a turbidimetric method, where barium chloride was added to form a barium sulfate precipitate and turbidity was measured spectrophotometrically, providing insight into sulfate levels which can affect taste and corrosiveness. Chlorides were analyzed using argentometric titration, where silver nitrate was added in the presence of potassium chromate as an indicator; the endpoint was marked by a distinct colour change. Total hardness (TH) was calculated by summing the measured concentrations of calcium and magnesium, giving a comprehensive measure of the water's mineral content. Total alkalinity (TA) was measured by titrating with a standard acid to determine bicarbonate and carbonate content, offering an indication of the water's buffering capacity, crucial for understanding its resistance to pH fluctuations. These standardized procedures were rigorously applied to ensure consistency and reliability in evaluating the quality and suitability of the water samples for different applications.

The contamination levels in soil were assessed through the following indices: the geo-accumulation index (I_{geo}), enrichment factor (EF), contamination factor (Cf) and degree of contamination (CD), following established methods (Buat-Menard and Chesselet, 1979; Jeffery, 1981). For the background values of the different element in earth surface, Truekian and Wedephol (1961) method was used. The I_{geo} was computed using the equation $I_{\text{geo}} = \log_2 (C_n / 1.5 B_n)$, where C_n is the measured concentration of a metal in soil, and B_n is its background concentration, with 1.5 as a factor to account for potential natural variability (Lokeshwari and Chandrappa, 2006; Fagbote and Olanipekun, 2010). The values of I_{geo} less than 1 indicates unpolluted soil, values between 1 to 5 indicates moderate to highly polluted soil and values greater than 5 indicates very high polluted soil (Nimick and Moore, 1991) (see Table 1). The EF was determined as $EF = (C_n / C_{\text{ref}}) (B_n / B_{\text{ref}})$, where C_{ref} and B_{ref} represent concentrations of a reference element (often iron or aluminium) in soil and its background, respectively, to assess anthropogenic influence (Lăcătușu, 1998; Atgn et al., 2000; Huu et al., 2010). The Cf was calculated by the ratio $Cf = C_n / B_n$, indicating the level of metal contamination relative to background levels (Harikumar et al., 2009). A value of Cf less than 1 is a low contamination factor while greater than 6 is a very high contamination factor (see Table 2). Finally, the CD was obtained by summing the Cf values for each metal,

expressed as $CD = \sum C_{fi}$, representing the cumulative contamination level across multiple metals. These indices provide a multi-faceted approach to understanding the extent and source of soil contamination.

Table 1. The seven classes of geo-accumulation index (I_{geo}) by **Nimick and Moore (1991)**

Classes	I_{geo} class	Value of soil quality
1	< 0	Unpolluted
2	0-1	Unpolluted to moderately polluted
3	1-2	Moderately polluted
4	2-3	Moderately to highly polluted
5	3-4	Highly polluted
6	4-5	Highly polluted to very highly polluted
7	> 5	Very highly polluted

Table 2. Classification of contamination factor (Cf) by **Muller (1969)**

Class	Contamination Factor	Description of contamination factor
1	< 1	Low
2	1-3	Moderate
3	3-6	Considerable
4	> 6	Very high

The pollution load index (PLI) is calculated using the formula: $PLI = (CF_1 \times CF_2 \times \dots \times CF_n)^{1/n}$ where CF represents the contamination factor for each element, and n is the total number of elements (**Tomlinson et al., 1996; Yang et al., 2011**). For this study, assuming the contamination factor (CF) values are provided, the CFs for Fe, Zn, Pb, Cr and As are multiplied together, and the fifth root ($n = 5$) is taken. A PLI value greater than 1 indicates pollution in the area (**Córdoba-Tovar et al., 2023**), with the index reflecting pollution levels ranging from moderate to very high. The potential ecological risk index (PERI) for this study is calculated by summing the ecological risk factors (Eri) for each potentially toxic element (PTE) using the formula: $PERI = \sum (Tr_i \times CF_i)$, where Tr is the toxic response factor and CF is the contamination factor for each element. The PERI highlights the overall ecological risk, with significant contributions from elements such as lead (Pb) and arsenic (As) due to their higher contamination factors.

Principal component analysis (PCA) was employed to reduce the dimensionality of contamination indices and identify key contributors to variance in the dataset, following established protocols for environmental data analysis (**Jolliffe and Cadima, 2016**). The principal component analysis (PCA) was performed on contamination indices derived from both soil and water data, specifically the geoaccumulation index (I_{geo}), enrich-

Table 3. Original data on determined concentrations of potentially toxic elements in mg/kg in soil samples. "BDL" indicates values below the detection limit

Sample Id	Fe (mg/kg)	Cd (mg/kg)	Cr (mg/kg)	Zn (mg/kg)	Pb (mg/kg)	As (mg/kg)
K4 S.S	1526	BDL	2.793	0.622	2.024	90.9
L4 S.S	2048	BDL	1.464	0.734	BDL	40.6
M4 S.S	2110	BDL	1.64	1.119	0.547	54.4
N5 S.S	6990	BDL	2.426	2.497	BDL	137.3
N4 S.S	2256	BDL	0.723	1.266	0.553	272.7
O5 S.S	3072	BDL	1.148	1.32	0.732	255
P5 S.S	1586.2	BDL	1.183	1.566	2.641	25.4
I5 S.S	884.8	BDL	1.097	0.964	3.41	15.4
H4 S.S	4774	BDL	2.128	4.826	BDL	295
G6 S.S	1070.2	BDL	1.737	1.215	2.808	30.37
G6 S.Sb	1664.2	BDL	0.949	1.427	2.015	135
G8 S.S	1639.6	BDL	0.739	1.461	2.04	BDL
F8 S.S	1474.4	BDL	0.886	1.543	0.864	75.7
F7 S.Sa	1573.2	BDL	1.173	1.722	1.982	BDL
F9 S.Sa	1319.4	BDL	1.013	1.6	1.053	BDL
F10 S.Sa	1349	BDL	1.197	1.688	1.157	BDL
E11 S.S	1880	BDL	1.17	1.088	1.936	57.7
F16 S.Sa	2992	BDL	1.167	1.598	2.408	29.8
F17 S.Sa	1609.8	BDL	1.28	0.868	1.326	167
E18 S.S	1409.8	BDL	0.599	1.086	0.673	BDL
F13 S.S	2206	BDL	BDL	1.133	2.822	BDL
L5 S.S	1662.6	BDL	BDL	0.98	2.044	202.4

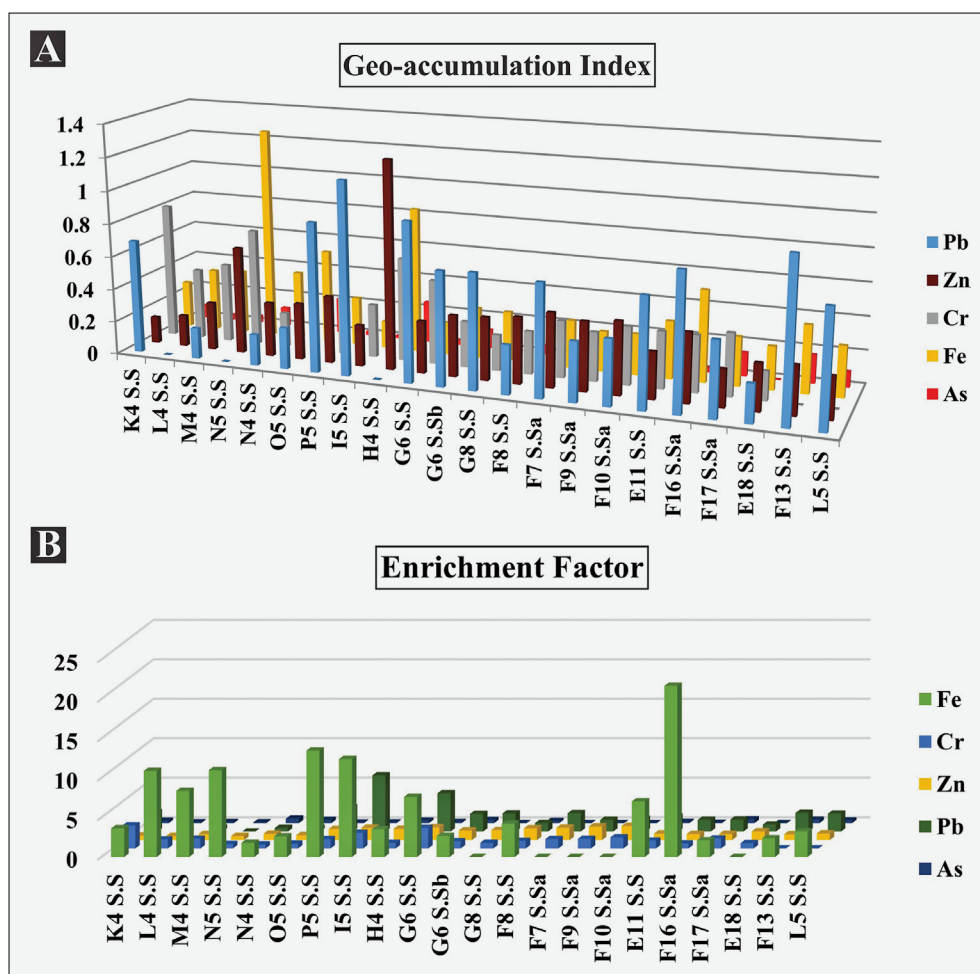


Figure 4. Results of the analyzed field data: (A) bar chart illustrating the I_{geo} values and (B) bar chart illustrating the EF values for Pb, Zn, Cr, Fe and As based on their concentration in soil samples

ment factor (EF) and contamination factor (Cf). These indices were calculated for both soil and water samples and subsequently used in the PCA to identify the primary contributors to variance in the dataset. The aim of the analysis was to capture and interpret the relationships between these indices across both environmental media. First, all variables for soil data, including the I_{geo} , EF and Cf, were standardized to a mean of zero and standard deviation of one. For the water data, similar indices were applied to assess water quality and contamination levels. Both datasets were standardized prior to PCA to ensure comparability, and the analysis was conducted to offer a comprehensive overview of contamination across the two media. This standardization ensured that variables with different scales contributed equally to the analysis. A covariance matrix was calculated to assess inter-variable relationships and reveal linear dependencies. Eigenvalues and eigenvectors of this matrix were then computed; eigenvalues indicate the amount of variance each principal component (PC) captures, while eigenvectors define the direction of each PC in relation to the original variables. The PCs were ordered by ei-

genvalue magnitude, with those capturing the highest variance retained for interpretation. This study selected PCs explaining over 80% of the total variance. To interpret PCA results, loadings derived from eigenvectors were examined to identify high-loading variables, indicating significant contributors to each PC. This was complemented by plotting PCA scores to visualize clustering patterns and contamination profiles. These steps allowed identification of elements most influential in contamination, guiding targeted remediation recommendations based on key contributors to variance (Jolliffe and Cadima, 2016). SPSS software was used for PCA analysis. The procedure for carrying out PCA is given in supplementary materials.

4. Results and Discussion

The results of the study indicate significant contamination of soil and water in the mining-affected area. Assessment of soil using indices, the I_{geo} , EF, Cf and CD, confirmed widespread pollution attributed to mining activities (see Figures 4A, 4B, 5A, 5B and Table 3). Based on the I_{geo} values (see Figure 4A), the highest pollution

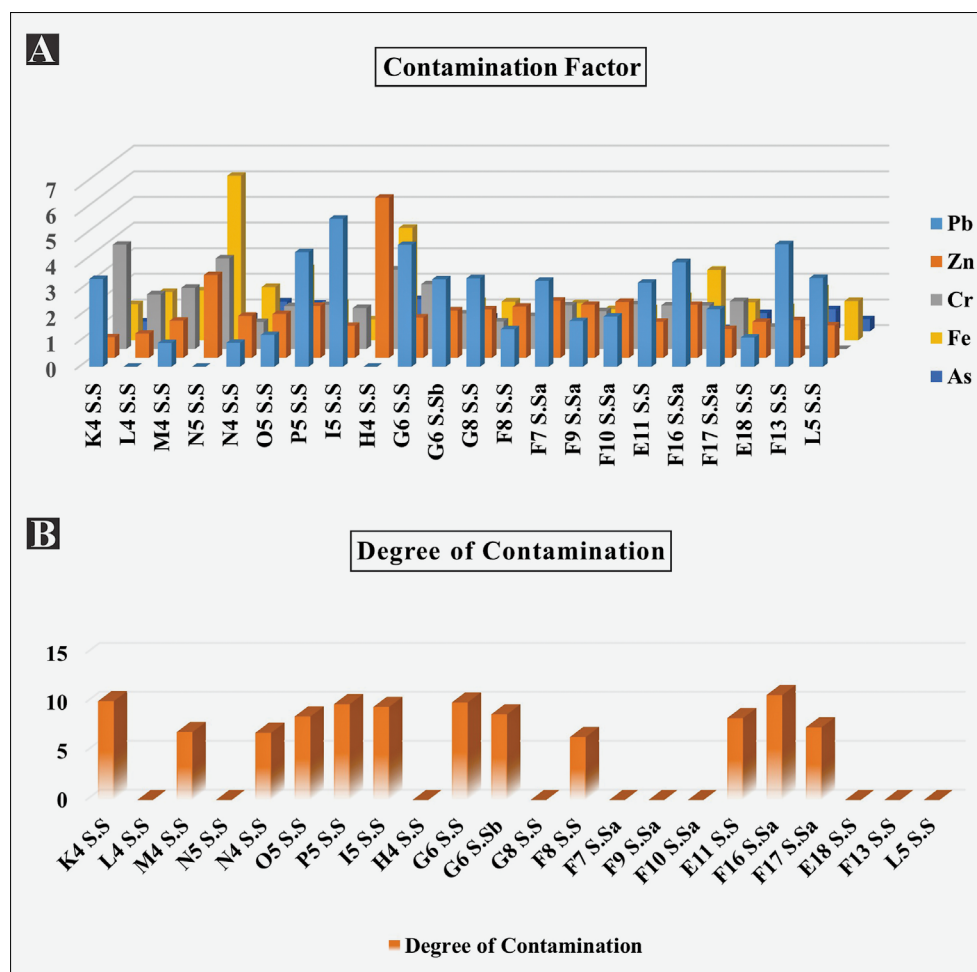


Figure 5. Results of the analyzed field data: (A) bar chart illustrating the Cf index values and (B) bar chart illustrating the CD values for Pb, Zn, Cr, Fe and As based on their cumulative contamination level in soil samples

is attributed to iron (Fe) with a value of 1.3, followed by zinc (Zn), lead (Pb), chromium (Cr) and arsenic (As), which has the lowest value at 0.3. This indicates a contamination order of $Fe > Zn > Pb > Cr > As$, suggesting moderate to strong pollution by Fe and low to moderate levels for the remaining elements. Similarly, EF values (see **Figure 4B**) show significant enrichment of Fe (maximum EF = 21.6), while Pb, Cr, Zn and As exhibit lower enrichment, with As recording the minimum EF of 0.4. These results also classify the area as moderately to highly contaminated. The Cf values (see **Figure 5A**) further support this trend, with Fe presenting the highest contamination factor of 6, followed by Zn, Pb, Cr and As which again shows a minimum Cf of 0.4. CD values of samples ranging between 8 and 11 (see **Figure 5B**) place the area under the moderate contamination category.

Soil samples analysis reveals that concentrations of Fe, Zn, Pb, Cr and As exceed acceptable limits according to standard PTE indices i.e., I_{geo} and Cf (see **Tables 1** and **2**), further confirming the impact of mining activities.

The PLI calculated for the study area is approximately 1.20, also indicating moderate contamination by

PTEs, as this value is slightly above the baseline (baseline PLI = 1.0). The potential ecological risk index (PERI), incorporating Cf values and toxic response factors, yields a value of 18. When compared to the value range ($PERI < 50$) defined for low potential ecological risk in standard ecological risk classification (e.g. **Hakanson, 1980**), this calculated value of PERI indicates a low ecological risk. Therefore, although the area is affected by PTEs from mining, the overall threat to ecosystem health remains limited. Nevertheless, the presence of elevated PTEs underscores the need for mitigation and management strategies to prevent further environmental degradation.

Principal Component Analysis (PCA) of the soil contamination data shows that Principal Component 1 (PC1) accounts for the majority of the variance, with high loadings from iron (Fe) and zinc (Zn), indicating that these elements are the primary contributors to soil contamination in the study area (see **Figure 6**). Principal Component 2 (PC2) explains additional variance, with significant contributions from lead (Pb) and chromium (Cr), suggesting their roles in soil pollution, though to a lesser

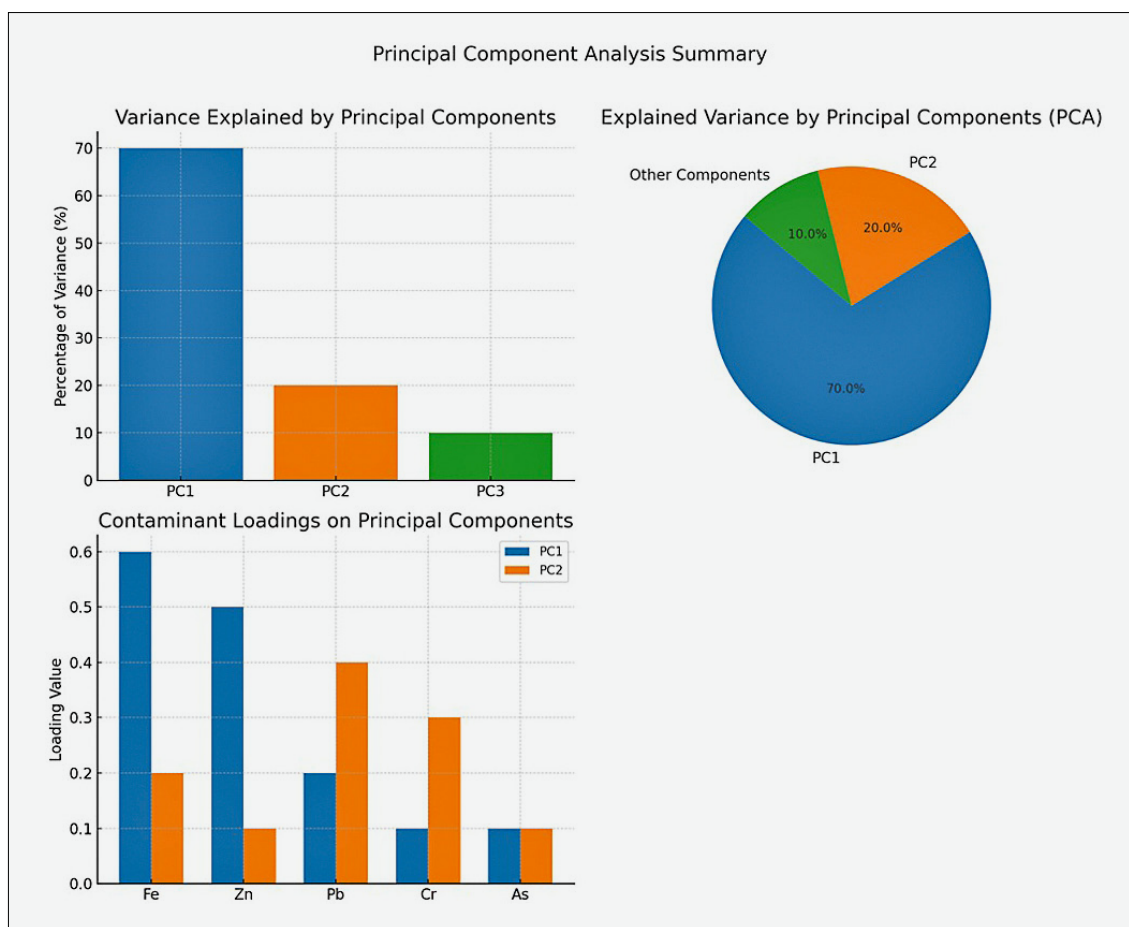


Figure 6. Results of the PCA analysis

Table 4. Comparison of water quality parameters from the present study with WHO recommendations

Parameters	WHO recommendations		Results of the present study (Average of 134 samples)		
	Desirable level	Maximum permissible level	Maximum	Minimum	Average
pH	7.5-8.5	9.2	8.7	3.1	7.4
TDS	Up to 500 mg/l	1500 mg/l	6150 mg/l	117 mg/l	1312.8 mg/l
EC	-	2500 μ s/cm	10000 μ s/cm	239 μ s/cm	3539.7 μ s/cm
Calcium	Up to 75 mg/l	200 mg/l	1362.5 mg/l	16 mg/l	214.4 mg/l
Magnesium	Up to 50 ppm	150 ppm	2690 ppm	1 ppm	451 ppm
Hardness as CaCO ₃	Up to 100 mg/l	500 mg/l	1680 mg/l	8 mg/l	438.4 mg/l
Sulphates	Up to 200 mg/l	400 mg/l	807.27 mg/l	33.9 mg/l	79.07 mg/l
Chlorides	Up to 200 mg/l	600 mg/l	2117.2 mg/l	16 mg/l	132.0 mg/l
Total hardness	Soft: < 75 mg/l	Hard: 150-300 mg/l Very hard: > 300 mg/l	3625 mg/l	31.74 mg/l	666.2 mg/l
TA	-	200 mg/l	2200 mg/l	40 mg/l	537 mg/l

extent. This analysis highlights Fe and Zn as the most critical contaminants, which should be prioritized in remediation efforts. The findings align with global studies, such as those by Al-Soudany et al. (2024) and Jawjit et al. (2024), which also examined soil contamination from industrial activities and urban waste. The contamination

in the Surghar Range is notably higher in Fe and Zn compared to regions like India and China, yet lower in Pb and Cr, aligning with reports from less polluted mining regions (Hakanson, 1980).

In terms of water quality, both laboratory and field-tested parameters exhibit considerable variability. Labo-

Table 5. Mean concentrations of PTEs in the soil based on present results and their comparison with the results of other's studies in the world

Mean Concentrations of PTEs in the soil (mg/kg)						
Region	Fe (mg/kg)	Cd (mg/kg)	Cr (mg/kg)	Zn (mg/kg)	Pb (mg/kg)	As (mg/kg)
This Study (Pakistan)	2140.78	BDL	1.32	1.46	1.73	117.79
Spain (Hudson-Edwards et al., 1999; Alvarez et al., 2003)	294	6.59	-	465.8	881.8	-
India (Prasad et al., 2014; Reza et al., 2015)	166.2	3.82	-	338.8	304.7	-
Iran (Pirsaheb et al., 2013; Ghaderpoori, 2018)	50	1.49	-	363.4	1002	-
China (Yuan et al., 2013; Duan and Tan, 2013)	198	11	-	1163	641.3	-
South Korea (Kim et al., 2001; Lee et al., 2005)	22.1	1.99	-	183.2	111.1	-
Vietnam (Thuy et al., 2000; Tra Ho and Egashira, 2000)	3.7	1.35	-	41.09	30635	-
PEC (Caeiro et al., 2005)	-	4.98	-	459	128	-
TEC (MacDonald et al., 2000)	-	0.99	-	121	35.8	-

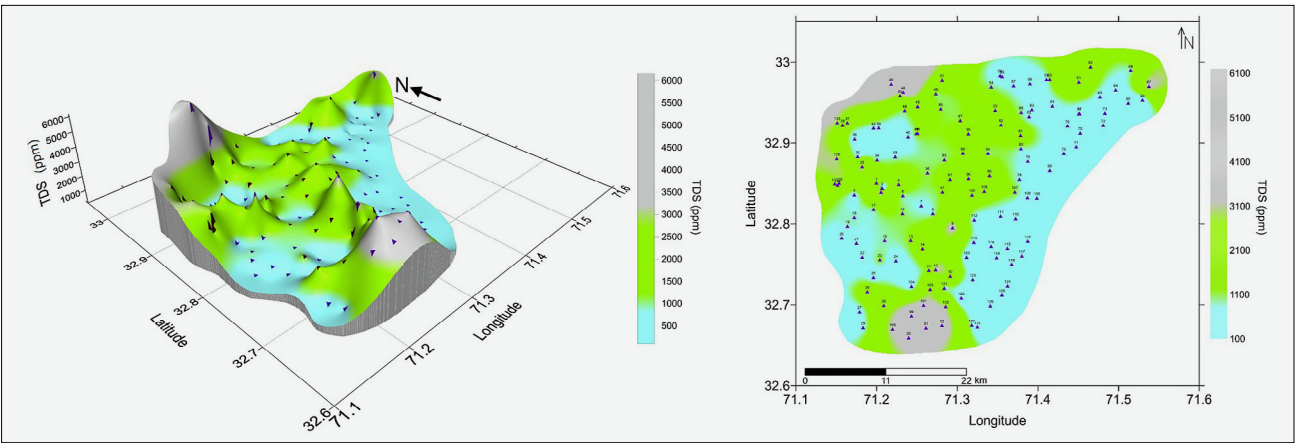


Figure 7. Depicting TDS from the collected field data: 3D surface plot (left) and 2D heatmap (right) representations of TDS results

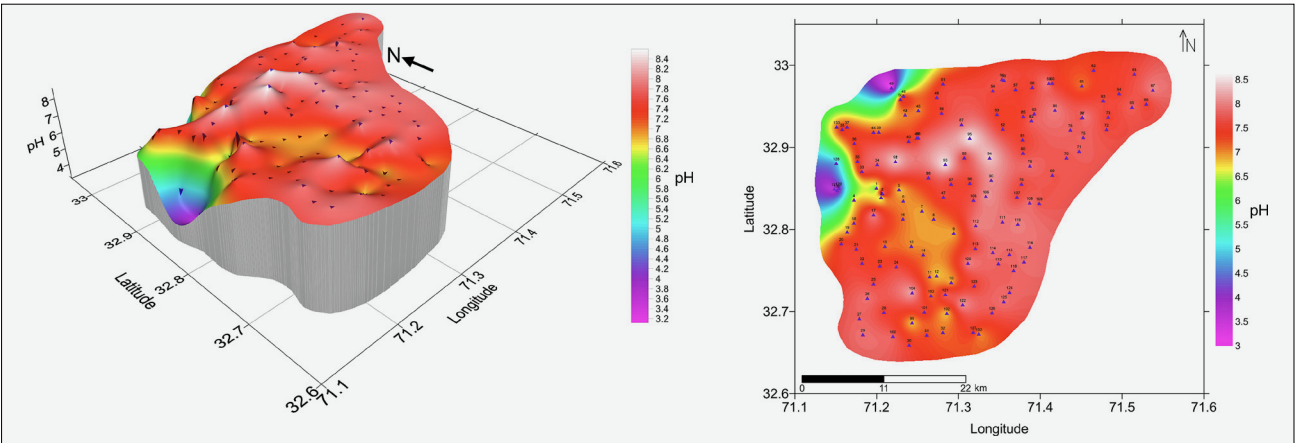


Figure 8. Depicting pH from the collected field data: 3D surface plot (left) and 2D heatmap (right) representations of pH results

ratory results show chloride concentrations ranging from 16 to 2117.22 mg/l (average 132 mg/l), total hardness (TH) from 31.74 to 3625 mg/l (average 666.2 mg/l), and total alkalinity (TA) from 40 to 2200 mg/l (average 537 mg/l). Calcium hardness ranges from 8 to 1680 mg/l (av-

erage 438.4 mg/l) and magnesium hardness from 0 to 2262.5 mg/l (average 443.95 mg/l), with calcium ions averaging 14.63 mg/l and magnesium ions averaging 106.55 mg/l. Carbonate concentrations range from 0 to 520 mg/l (average 104 mg/l) and bicarbonate concentrations from 0

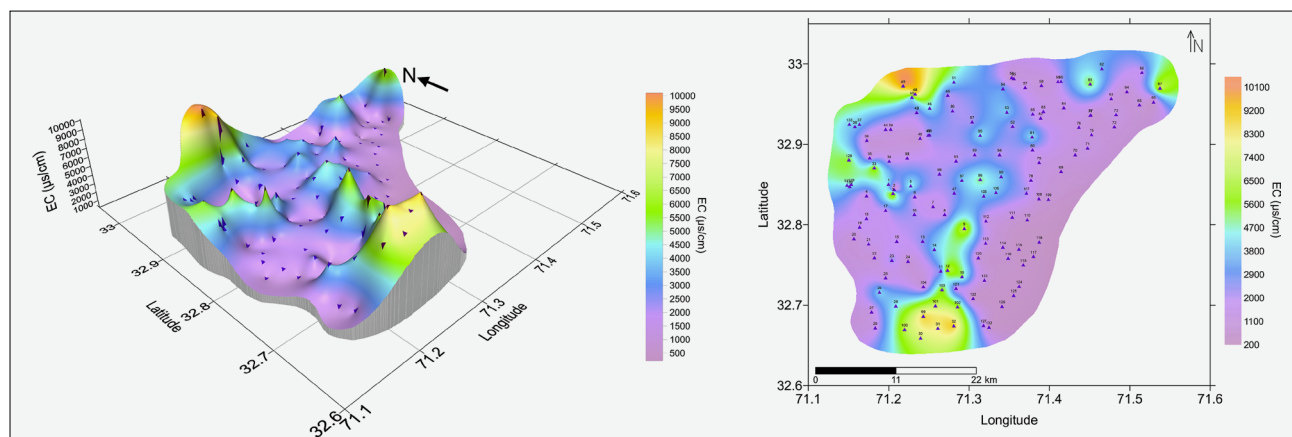


Figure 9. Depicting EC from the collected field data: 3D surface plot (left) and 2D heatmap (right) representations of EC results

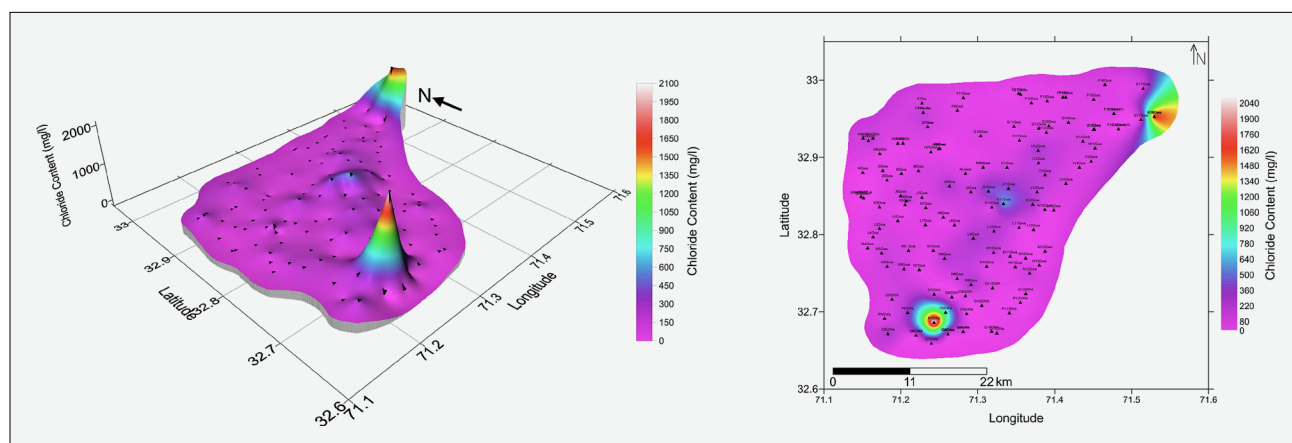


Figure 10. 3D surface plot (left) and 2D heatmap (right) representations of chloride concentrations for the collected samples

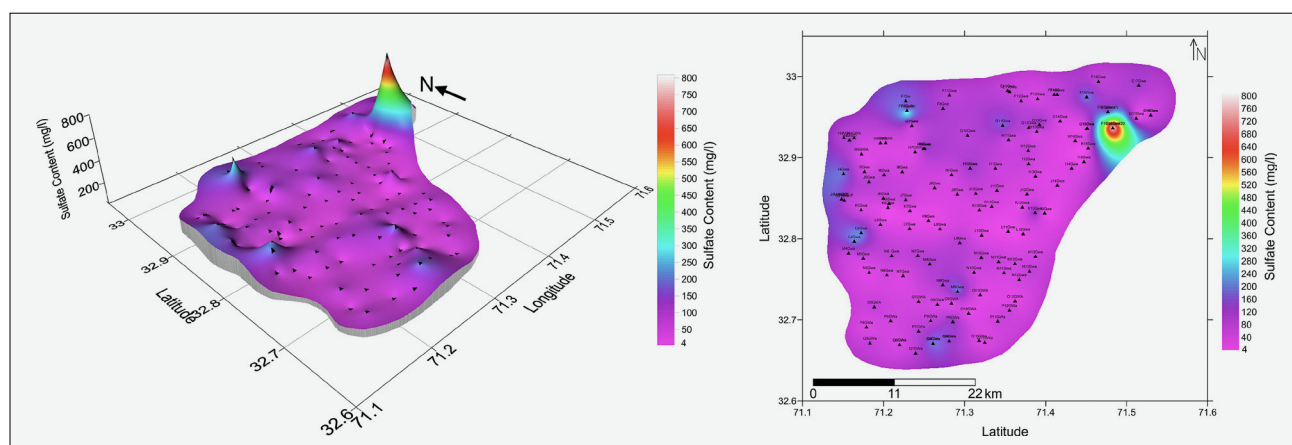


Figure 11. 3D surface plot (left) and 2D heatmap (right) representation of sulphate concentrations for collected samples

to 1680 mg/l (average 417.72 mg/l). Sulfate levels vary from 33.9 to 807.27 mg/l (average 79.07 mg/l), while hydroxide ions are absent. Field data show total dissolved solids (TDS) ranging from 117 to 6150 mg/l (average 1312.8 mg/l), electrical conductivity (EC) from 239 to

10,000 $\mu\text{S}/\text{cm}$ (average 3539.7 $\mu\text{S}/\text{cm}$), and pH from 3.1 to 8.7 (average 7.4), indicating generally neutral to slightly alkaline conditions. These results demonstrate considerable heterogeneity in water quality across the sampling locations (see **Table 4**). The deterioration of water quality,

marked by variations in parameters like TDS and pH, mirrors trends observed in other mining regions globally, including Spain and the United States (McLemore, 2017). Furthermore, the absence of cadmium (Cd) contamination of water contrasts with higher levels reported in other industrial areas (Zhang et al., 2011).

A comparison of the mean concentrations of PTEs in the soil of present study with the reported results worldwide is shown in Table 5. The significantly higher iron (Fe) levels in this study, compared to other regions shown, suggest either natural geochemical enrichment or anthropogenic contributions, warranting further investigation into local geological and industrial activities. Cadmium (Cd) being below detection limits highlights the absence of significant industrial or agricultural contamination, unlike the higher levels reported in Spain, China, PEC and India. The low concentrations of chromium (Cr), zinc (Zn) and lead (Pb) indicate minimal contamination relative to countries like Iran, India, China and Spain. However, the elevated arsenic (As) levels are concerning and could be linked to natural geochemical processes, such as arsenic-bearing minerals in the study area's lithology or localized human activities like mining or the use of arsenic-containing pesticides. These results suggest that mining activities have significantly elevated the levels of PTEs in the soil near the mining areas compared to the plains. Previous studies by Al-Soudany et al. (2024), Jawjit et al. (2024) and Saeed et al. (2024) have focused on enhancing expansive soils with water treatment sludge ash (WTSA), assessing urban hazardous waste risks, and stabilizing cadmium-contaminated soil using silica-rich alkaline activators. These studies highlight innovative waste reuse approaches for environmental protection and soil improvement.

Mining activities not only impact soil quality but also degrade water quality, as evidenced by the analysis of 134 water samples from the study area. Parameters such as TDS, EC, pH and temperature were measured on-site (see Table 4).

Comparison with WHO recommendations showed that water quality often exceeds permissible limits, with high levels of hardness (an average of about 666 mg/l), alkalinity, calcium and magnesium (WHO, 2020) (see Table 4). The water quality classification based on TDS 3D map indicates that the study area can be divided into different zones depending on fresh, slightly saline, moderately saline, very saline and brine water. The area near the Indus River has freshwater quality while as we move westward toward the Surghar Range, the TDS value increases and water quality changes from slightly saline to brine water. The southern part of the area which is tehsil Isa Khel of the Mianwali District also has very saline to brine water quality (see Figure 7, Table 4). The water quality classification based on pH 3D map shows that most areas had pH levels within WHO limits, but areas near mining activities exhibited acidic water due to high sulfur content associated with coal mining (see Figure

8, Table 4). The water quality classification based on EC 3D map indicates that values were high in areas with extensive mining activities and in the southern part of the study area, indicating poor water quality due to high dissolved ion content (see Figure 9, Table 4). In addition to these, high concentrations of chlorides and sulphates in water are also determined in the study area (see Figures 10 & 11, Table 4).

5. Conclusions

1. Analysis of soil samples revealed elevated levels of PTEs, including Pb, Zn, Cr, Fe and As surpassing acceptable limits in the order of iron (Fe) > zinc (Zn) > lead (Pb) > chromium (Cr) > arsenic (As).
2. The pollution load index (PLI) was calculated using the contamination factors (CFs) of Fe, Zn, Pb, Cr and As to assess the pollution level in the study area. A PLI value of 1.20 suggests moderate contamination by PTEs, implying that the region is slightly contaminated and therefore there is a need for environmental remediation.
3. The potential ecological risk index (PERI) was also determined set to assess the ecological threat these PTEs present. A PERI value of 18 indicates a minimal environmental risk; thus, contamination by PTEs is not expected to cause major ecological harm.
4. Principal component analysis (PCA) identified key sources of contamination, with the first principal component (PC1) showing that Fe and Zn are the primary contributors to soil pollution of the study area, while PC2 highlighted the roles of Pb and Cr, but to a lesser degree. This analysis underscores the importance of Fe and Zn as the most critical contaminants, informing the direction of remediation efforts.
5. Comparison of water quality results with WHO recommendations showed that the observed water quality parameters often exceed permissible limits, with high levels of hardness, alkalinity, TDS, calcium and magnesium concentrations. Similarly, regional comparison of mean concentration of PTEs of present study indicates elevated levels compared to other regions.
6. Three-dimensional models constructed based on total dissolved solids (TDS), pH, electrical conductivity (EC), chlorides and sulphates concentrations of water samples are a reliable way to demarcate the hazardous areas efficiently. The results show that areas near the extreme western side of study area where various mining activities occur, have higher levels of PTEs compared to the plains farther from these areas.

In summary, the present study highlights the significant environmental impact of anthropogenic activities, including mining operations, industrial discharges and

urbanization emerging as key contributors to the contamination of soil and water by potentially toxic elements (PTEs), particularly Fe, Zn and Pb. These elements were identified as the primary pollutants of concern, while Cr and As also warrant proactive monitoring and management. Elevated concentrations of PTEs were consistently observed in proximity to mining sites, highlighting the localized yet intense influence of such activities. Furthermore, acid mine drainage (AMD) exacerbates the situation by degrading environmental quality and increasing the mobility and bioavailability of PTEs, thereby posing further risks to ecosystem and human health.

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SAŽETAK

Procjena opasnosti od rudarskih aktivnosti u području Surghar, Punjab, Pakistan

Ova studija istražuje utjecaj eksploatacije ugljena na okoliš na lokaciji Surghar Range, Punjab, Pakistan, s naglaskom na onečišćenje tla i podzemne vode potencijalno toksičnim elementima (PTE). Kako bi se procijenio opseg i definirali izvori onečišćenja, prikupljena su i analizirana 22 uzorka tla i 134 uzorka vode korištenjem standardnih fizičko-kemijskih i geokemijskih metoda. Ova studija identificirala je željezo (Fe), cink (Zn) i olovo (Pb) kao primarne PTE-e koji su posljedica antropogenoga utjecaja, dok se krom (Cr) i arsen (As) također pojavljuju u povišenim koncentracijama na određenim lokacijama. Prema iznosima koncentracija u tlu utvrđen je redoslijed PTE-a: Fe > Zn > Pb > Cr > As. Indeksi onečišćenja otkrili su umjerene do visoke razine onečišćenja, s indeksom opterećenja onečišćenjem (PLI) od 1,20, što upućuje na ukupno umjereno onečišćenje. Iako je indeks potencijalnoga ekološkog rizika (PERI) bio relativno nizak, odnosno 18, koncentracije određenih PTE-a premašile su međunarodno definirane granične vrijednosti upućujući na potrebu sanacije okoliša. Analiza glavnih komponenti (PCA) identificirala je Fe i Zn kao dominantne uzročnike onečišćenja. Analiza podzemne vode pokazala je prostornu promjenu kvalitete vode: uzorci u blizini rijeke Ind bili su kvalitete slatke vode, dok su se razine saliniteta povećavale prema zapadu, prema zoni eksploatacije, tako da je u Tehsil Isa Khelu utvrđen salinitet koji odgovara salinitetu slane vode. Voda u blizini rudarskih područja pokazala je niži pH i višu električnu vodljivost (EC), što upućuje na kisele rudničke vode, odnosno utjecaj ugljena bogatoga sumporom. Komparativna analiza s globalnim rudarskim regijama otkrila je kako su prosječne koncentracije PTE-a u Surghar Rangeu znatno više, što naglašava potrebu za provedbom održivih rudarskih praksi i ciljanim strategijama upravljanja okolišem kako bi se zaštitili tlo i vodni resursi.

Ključne riječi:

eksploatacija ugljena, opasnosti za okoliš, potencijalno toksični elementi (PTE), kvaliteta vode, onečišćenje tla

Authors' Contribution

Syed Sajjad Ahmad (MS, Deputy Director) has done formal analysis and investigation; and wrote the original draft. **Hafiz Muhammad Zaheer Afzal** (MS, Assistant Director) has done writing and reviewing. **Hafiz Zeeshan Akram** (MS, Assistant Director) has done writing and reviewing. **Sajjad Khan** (PhD, Deputy Director) has done the interpretation; writing and reviewing. **Ihtisham Islam** (PhD, Lecturer) has done writing and reviewing. **Salman Ahmed Khattak** (MS, Lecturer/Researcher) has done formal analysis and investigation, writing, reviewing and wrote the original draft. All co-authors made substantial contributions, read and commented on several versions of the manuscript, and agreed with the contents of the manuscript.