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**Zafar Ali**
University of Sindh
**Farah Naz Talpur**
University of Sindh
**Hassan Imran Afridi**
University of Sindh
**Habibullah Abbasi**
habibullah.abbasi@usindh.edu.pk
University of Sindh
**Shahjahan Shabbir Ahmed**
Balochistan University of Information Technology
**Nazir Ahmed Brohi**
University of Sindh

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# Geochemical Distribution and Transfer of Heavy Metals in Water, Soil, and Mazari Palm (*Nannorrhops ritchiana*) in the Mountainous Region, Balochistan

Zafar Ali[2], Farah Naz Talpur[1], Hassan Imran Afridi[1], Habibullah Abbasi[3*], Shahjahan Shabbir Ahmed[4] Nazeer Ahmed Brohi[5]

[1]National Centre of Excellence in Analytical Chemistry, University of Sindh, Jamshoro -76080, Pakistan

[2]Chemistry Department, University of Turbat, Balochistan- 92600, Pakistan

[3]Center for Environmental Sciences, University of Sindh, Jamshoro, Pakistan

[4]Department of Biotechnology and Informatics, Balochistan University of Information Technology, Engineering and Management Sciences, Quetta 87300, Pakistan.

[5]Microbiology department, University of Sindh, Jamshoro, Pakistan

**Corresponding author:** Habibullah Abbasi (habibullah.abbasi@usindh.edu.pk)

## Abstract

Heavy metal contamination in environmental resources, such as water, soil, and Mazari palm (*Nannorrhops ritchiana*). Mineral-rich landscapes, particularly in mountainous regions, are highly vulnerable. Prior research studies have not considered the dynamic processes and transfer of heavy metal pollution in these environmental resources.

This research introduces a dynamic approach for assessing heavy metal contamination in water, soil, and Mazari palm (*Nannorrhops ritchiana*), providing critical insights into heavy-metal contamination in arid environments and establishing a foundation for future monitoring and environmental risk assessment.

The study applied the Heavy Metal Pollution Index (HPI) for water, the Geoaccumulation Index (Igeo) for soil, and the Transfer Factor (TF) for the indigenous Mazari palm (*Nannorrhops ritchiana*) to evaluate the contamination levels. The results for HPI analysis indicated that Zinc (Zn), nickel (Ni), and Molybdenum (Mo) were major contributors, and Iron (Fe), Lead (Pb), and aluminium (Al) reflected marked spatial variability in river water contamination. The Igeo analysis of soil samples indicated that Cu, Cr, and Zn are extremely high in the soil sources. In contrast, Co and Sb ranged from moderately to extremely contaminated. Nickel (Ni) consistently indicated heavy pollution, and molybdenum (Mo) showed moderate to heavy pollution. However, Mn and Fe were classified as unpolluted. This pattern indicates that Cu, Cr, and Zn are the most critical contaminants contributing to soil pollution in the study area. TF values showed that Mazari palm (*Nannorrhops ritchiana*) leaves exhibited negligible transfer of Al, Fe, Cu, Cr, Ni, and Co but indicated exceptionally high molybdenum (Mo) uptake (TF 2.68–7.00), which was further supported by EDX spectral analysis.

**Keywords:** Rocky Mountains, heavy metal pollution, Geo-accumulation index, Heavy Metal Pollution Index (HPI), Normalised Difference Vegetation Index (NDVI)

## 1. Introduction

Heavy metal pollutants are the most common environmental pollutants, resulting from natural and anthropogenic sources. Heavy metal pollution in water, soil, and palm trees is an indicator of environmental pollution. Therefore, heavy metal pollution indices are vital tools for evaluating contamination levels in ecosystems. These indices are crucial indicators for assessing heavy metal contamination in aquatic environments, soil, and vegetation. Soil and plant interactions and ecological indices have been widely applied to assess contamination patterns, which are predominantly governed by lithogenic processes.

The movement and transfer of heavy metal contamination are influenced by several environmental factors, such as variations in heavy metal composition and characteristics, pH, temperature, leaching duration and type, organic and inorganic ligand concentrations, and redox reactions. Temperature variations play an important role in the transfer of heavy metal contamination (J. Xu, Zhou, Chang, & Qu, 2006). Key climate drivers, including temperature, wind, and precipitation, act as drivers of sulphide oxidation, mobilizing particulates, and enhancing leaching, intensifying heavy metal contamination in copper mining regions (Punia, 2021). Seasonal variations and rising temperature trends in mountain ecosystems accelerate atmospheric metal contamination, with higher Pb concentrations in alpine vegetation during winter and early spring and elevated Al levels in acidified habitats. Snow-free catchments expand under global warming; earlier and broader dispersal of these metals into sub-mountain regions poses increasing ecological and health risks (Janiga, 2008). It was also observed that concentrations of copper, zinc, and sulphate in Colorado's mountain streams have approximately doubled over the past 30 years due to rising temperatures, which affect the natural chemical weathering of bedrock (Manning, Petach, Runkel, & McKnight, 2024).

The HPI helps in estimating the extent of heavy metal pollution in water. It accounts for different types of metals in the water and provides an overall score to determine whether the water is safe for use. If the score exceeds 100, the water may be unsafe. For instance, a study along the southwest coast of Ghana found that, although the highest metal concentrations in the water were within safe limits, lead (Pb) levels were concerning. The HPI score indicated that the water could be unsafe due to heavy metal pollution (Appiah-Opong et al., 2021). The geo-accumulation index (I<sub>geo</sub>) is widely used to assess heavy metal contamination in sediments. Previous studies have shown that sediments are mainly affected by arsenic (As), followed by cadmium (Cd), lead (Pb), zinc (Zn), and copper (Cu), with Arsenic(As) exhibiting the highest enrichment factor (EF=187.45), indicating severe pollution, while Cd, Pb, Zn, and Cu showed comparatively lower enrichment levels (EF = 100.59, 20.32, 12.42, and 3.46, respectively (Shafie et al., 2013). The transfer factor (TF) is essential for measuring the movement of heavy metals from soil to plants, such as palm trees. Plants with high TF values indicate that plants are efficiently absorbing metals, which is a potential risk for humans and animals through consumption of those plants (Mirecki, Agic, Sunic, Milenkovic, & Ilic, 2015). Mazari palm (Nannorrhops ritchiana) accumulates multiple heavy metals with a bio-concentration factor (BCF) greater than 1, specifically arsenic (As), copper (Cu), zinc (Zn), nickel (Ni), cobalt (Co), mercury (Hg), lead (Pb), chromium (Cr), cadmium (Cd), and manganese (Mn), confirming its efficiency as a phytoremediation agent in contaminated environments (Z. Ali et al., 2025).

No study has been conducted in the Makran region to investigate heavy metal pollution and its impacts. This study aims to investigate heavy metal pollution in Makran's mountain ecosystems by applying pollution indices such as HPI for water, Igeo for soil, and TF for Mazari palm, as well as analysing vegetation decline using a Normalised

Difference Vegetation Index (NDVI) map. The research study contributes to understanding the dynamics of heavy metal pollution transfer in environmental resources.

## 2. Materials and Methods

### 2.1. Study Area

Balochistan is a rocky, mountainous region rich in mineral reserves. The region has substantial deposits of coal, sulphur, chromite, iron ore, barite, marble, quartzite, and limestone. It exhibits abundant and valuable mineral resources like Cu and Au, which hold enormous potential for regional and national development (Jahangir & Javaid, 2015; Muhammad Sadiq Malkani, 2020; M Sadiq Malkani, Mahmood, Shaikh, & Arif, 2017). The geographical landscape of the region is mainly characterised by the Rocky Mountains and notable mineral deposits (Fig. 2). The region also features the Mazari palm (*Nannorrhops ritchiana*), located in rugged terrain between the Makran coastal range and the Central Makran range (Laeeq & Hassan, 2012). The Mazari palm is a bio-indicator, reflecting the geological environment of its habitat and highlighting metal mobility and exclusion mechanisms. It is a resilient species in extreme environmental conditions in Balochistan's arid landscapes (Naseem, Naseem, Bashir, Shirin, & Sheikh, 2005). The study area exhibit soil types, including loam, clay loam, and clay (Fig.2). Table 1 shows six selected sampling locations.

Table 1. Locations for sampling

| Site | Latitude | Longitude | River |
|---|---|---|---|
| S-I | 26.29647 | 63.12053 | Nehing |
| S-II | 26.25763 | 62.58768 | Kech Kor |
| S-III | 26.10047 | 62.24748 | Buleda |
| S-IV | 26.47459 | 65.2679 | Dasht |
| S-V | 26.11494 | 62.03433 | Panjgore (Rakshan River) |
| S-VI | 26.9706 | 64.08868 | Awaran (Gishkore) |

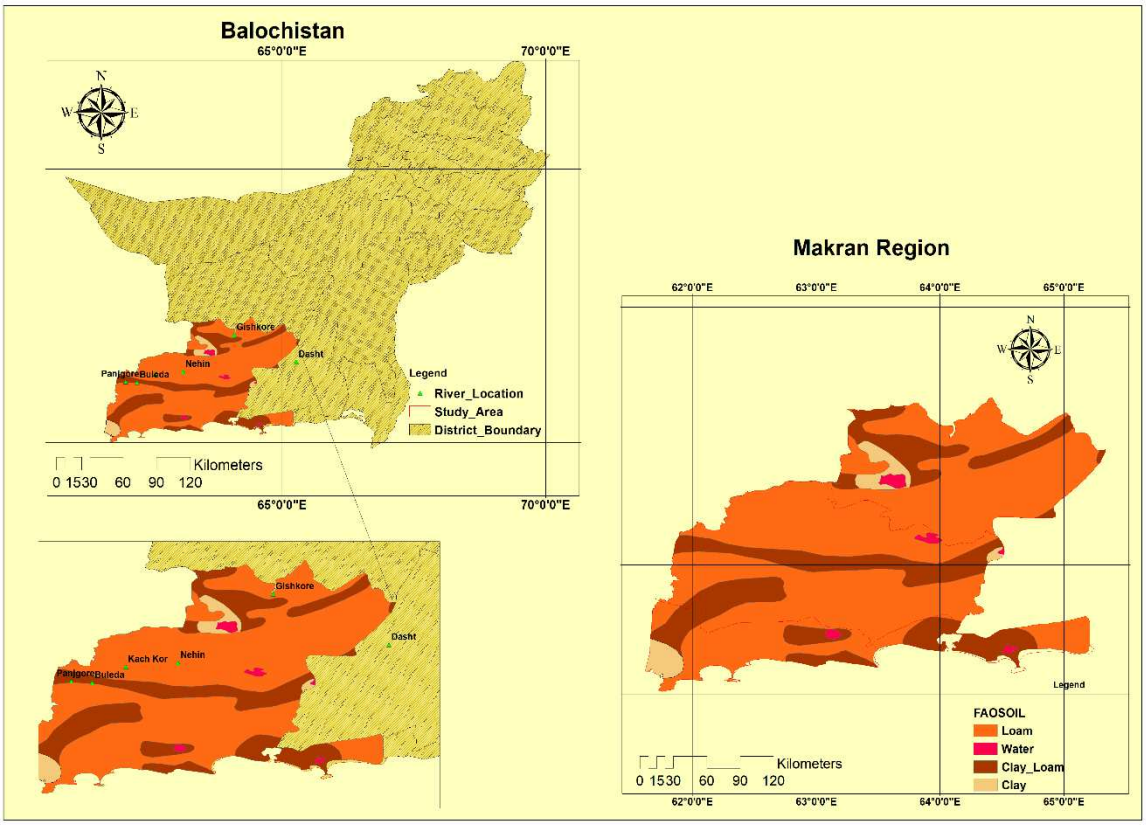



Fig. 1 study area map

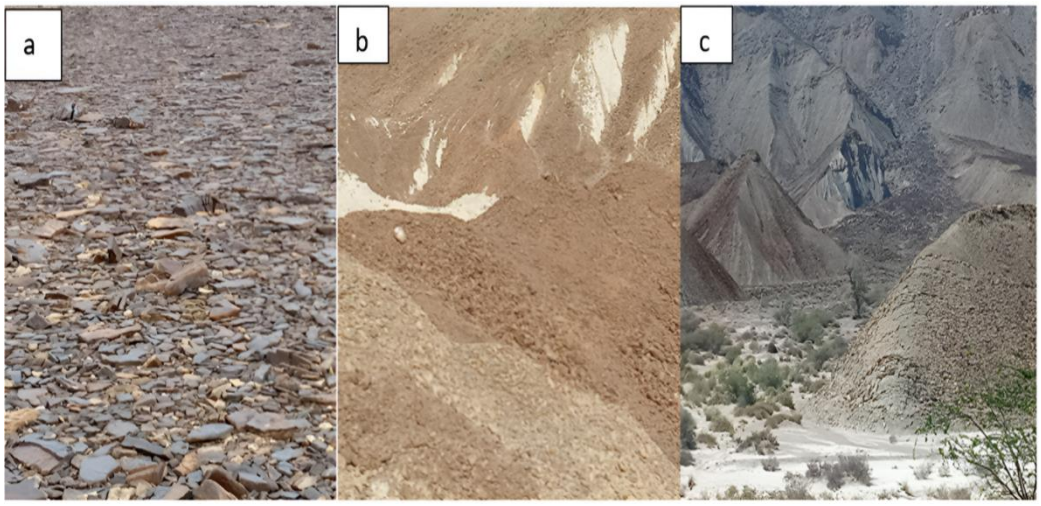



Fig.2 Study area views: (a) mountainous landscape showing black burned stones, (b) eroded hills with layered sediments, and (c) rocky terrain with angular fragments

## 2.2. Study Design and Sample Collection

The study determines the heavy metal contamination in water, soil, and Mazari palm trees in the Makran region. Climatic factors, such as temperature and rainfall records, were analyzed to assess the dynamic influence contributing to metal transport. Mathematical models were applied to evaluate heavy metal pollution, and a Normalised Difference Vegetation Index (NDVI) map was developed to assess the impact on vegetation.

Samples were collected three times at six selected stations in the study area. Water samples (n=18) were collected from the seasonal rivers at depths of 0.16-0.32 feet and placed in 1.5 L polythene bottles. Similarly, soil samples (n=18) were collected using an auger from 0-20 cm depth, labelled, and transported to the laboratory for analysis. Representative specimens of wild *Nannorrhops ritchiana,* including leaves, flowers, fruits, and fruit-bearing branches, were collected from Azaiyan, Tump, Kech District, Balochistan, Pakistan. The specimens were deposited at the National Herbarium of Pakistan, Pakistan Agricultural Research Council (PARC), Islamabad, for taxonomic verification and assignment of an accession number.

## 2.3. Laboratory Analysis

Initially, water samples were acidified with 1 M nitric acid ($HNO_3$) at a ratio of 2 ml/L and were concentrated 10-fold by evaporation at 80°C on an electric hot plate in a fume hood. After concentration, the water samples were filtered and diluted ten times with deionised water. Soil samples were mixed, gently crushed, and sieved through a 2 mm mesh to obtain a representative sample. Leaf samples were shade-dried for five weeks, washed, and crushed into a fine powder. Leaf and soil samples weighing 0.5 g were added to a conical digestion flask with 6 ml of nitric acid ($HNO_3$). The digestion flasks were heated on a hot plate at 150°C until the acid had evaporated. Once fumes arose, 1 ml of hydrogen peroxide ($H_2O_2$) was added to each flask. The flasks were then cooled, and the resulting colourless solution was diluted with 50 ml of Deionised water. The flasks were stored at 25°C overnight. The samples were digested and analysed according to the methods described (Ayrault, 2005; Oliva, Raitio, & Mingorance, 2003; Zarcinas, Cartwright, & Spouncer, 1987) .

## 2.4. Sample analysis and quality control

For the quantitative determination of heavy metal concentrations, the samples underwent acid digestion in accordance with standard protocols and were analysed using Inductively Coupled Plasma–Optical Emission Spectroscopy (ICP-OES). This method was selected for its high sensitivity and ability to detect trace levels of multiple metals simultaneously with precision. The filtrates were analysed for heavy metals using a Thermo Scientific ICAP 7000 Plus Series Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES), Thermo Scientific, Cambridge, UK. The instrument was fitted with a high-resolution Echelle polychromator, a large-format programmable array detector (L-PAD), and a ceramic nebuliser. The operating conditions for ICP-OES were optimised with a flush pump rate of 100, an analysis pump rate of 50, a pump stabilisation time of 5 minutes, RF power set at 1150 W, an auxiliary gas flow rate of 0.5 L/min, a nebuliser gas flow rate of 0.7 L/min, and a sample uptake rate of 0.8 L/min. Standards of 0.01, 0.1, 1.0, 10.0, 50.0, and 100 ppm were prepared from 100 ppm stock solutions of all elements. The glassware and other equipment were sterilised by immersing them in a 20% nitric acid ($HNO_3$) solution for 24 hours, then rinsed with deionised water. They were oven-dried at 60°C and stored in a dust-free environment. The performance was evaluated using Linear calibration curves with $R^2$=0.99.

## 2.5. Normalised Difference Vegetation Index (NDVI)

A workflow for generating a Normalised Difference Vegetation Index (NDVI) map of the Study Area was employed. Landsat Satellite imagery was acquired, mosaicked, and pre-processed. Relevant bands were extracted, and spectral radiance conversion was performed. NDVI was calculated using the NIR and red bands. Satellite images provide a wealth of valuable data that can be analysed and enhanced through various techniques (Huang, Tang, Hupy, Wang, & Shao, 2021; Nagler, Glenn, & Hinojosa-Huerta, 2009). NDVI is utilised to assess vegetation health due to its direct correlation with the plant canopy (Chowdhury et al., 2024). NDVI measures the amount of absorbed visible and infrared light, which is why NDVI utilises the RED and NIR bands of Landsat images, and the equation can be represented mathematically as

$$\boldsymbol{NDVI} = \frac{(\boldsymbol{NIR} - \boldsymbol{RED})}{(\boldsymbol{NIR} + \boldsymbol{RED})}$$

The NDVI values obtained are always in the range of -1 to +1. Whereas index values of -1 to 0 indicate no vegetation, those above zero indicate vegetation, and those between 0.6 and +1 indicate healthy and dense vegetation.

## 2.6. Statistical Analysis

Analysis of Variance (ANOVA) was used to statistically compare temperatures, rainfall and heavy metal levels across six stations. To evaluate the equality of variances among results from different stations, a test for homogeneity of variances was carried out at the 95% confidence level ($P < 0.05$). Visual representations of heavy metal concentrations and various risk metrics were produced using Microsoft Excel 2016 and SPSS 22 (SPSS Inc., Chicago, IL, USA). Data were analysed and presented as the mean and standard deviation of triplicate measurements. Additionally, ArcGIS (v. 10.5) software was utilised to create soil and NDVI maps.

# 3. Result

## 3.1 Heavy Metal Pollution in Water

The results for all six water HPI stations are presented in Table 1. The HPI is a metric that assesses the overall impact of dissolved heavy metals in water. The HPI results for drinking water must be below 100 to indicate an acceptable level of pollution (Prasad & Sangita, 2008). This index was first developed by Mohan et al. (1996) (Edet & Offiong, 2002; Herojeet, Rishi, & Kishore, 2015). It is used to determine whether a water sample is contaminated with heavy metals. The HPI formula comprises two components: unit weight and sub-index value. The unit weight (Wi) is proportional to 1/Si or Wi= K/?, where K is a constant, and Si is the standard permissible limit for the ith parameter. Similarly, the sub-index value Qi=Imi-Ii/(Si-Ii)*100. Different agencies specify standards for various heavy metals in water, such as the EPA (National Primary Drinking Water Standards (200)), the WHO (World Health Organisation for Drinking Water Quality (2008)), and the BIS (Bureau of Indian Standards (2012)). The Heavy Metal Pollution Index (HPI) classifies water quality into three categories: low heavy metal pollution (HPI <100), pollution at the risk threshold (HPI = 100), and high heavy metal pollution

(HPI > 100). Fig 3 and Fig 4 show the metal concentration and correlation of metal pollutants in water sample for each station obtained using laboratory analysis, respectively.

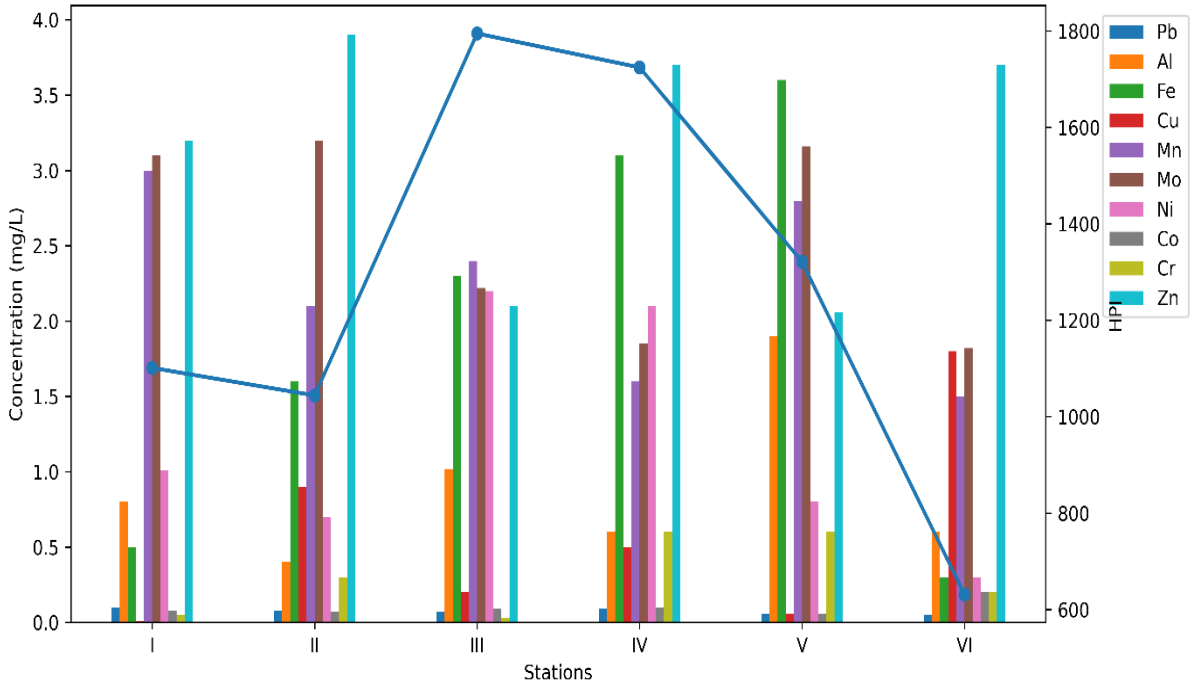



Fig 3. Concentration for heavy metal in water sample in correlation of HPI

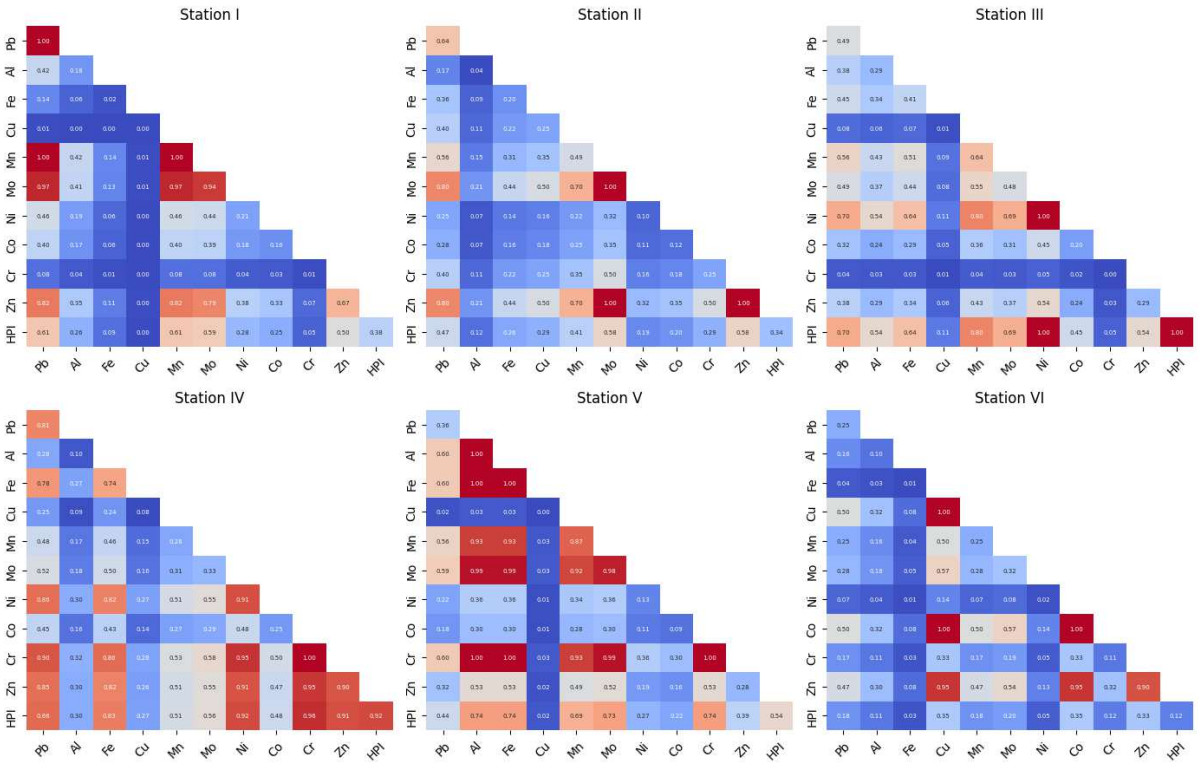


Fig 4. Correlation analysis of heavy metal concentration in the water samples.

## 3.2. Heavy Metal Pollution in Soil

Heavy metal pollution intensity in sediments was determined using the geo-accumulation index. The Igeo is the indicator used to gauge the extent of contamination and heavy metal enrichment in sediments and soils. Estimating the accumulation of heavy metals in soil was obtained from heavy metal data and typical laboratory analytical data using equation 1,

$$Igeo = Log2\left[\frac{Cn}{1.5\ Bn}\right] \qquad (1)$$

Where

$Cn$ is the total weighted average concentration of all heavy metals in the mine soil (mg/kg), and $Bn$ is the background level of heavy metal elements in the soil. Fig 5 shows the correlation of heavy metal pollutants obtained using laboratory analysis.

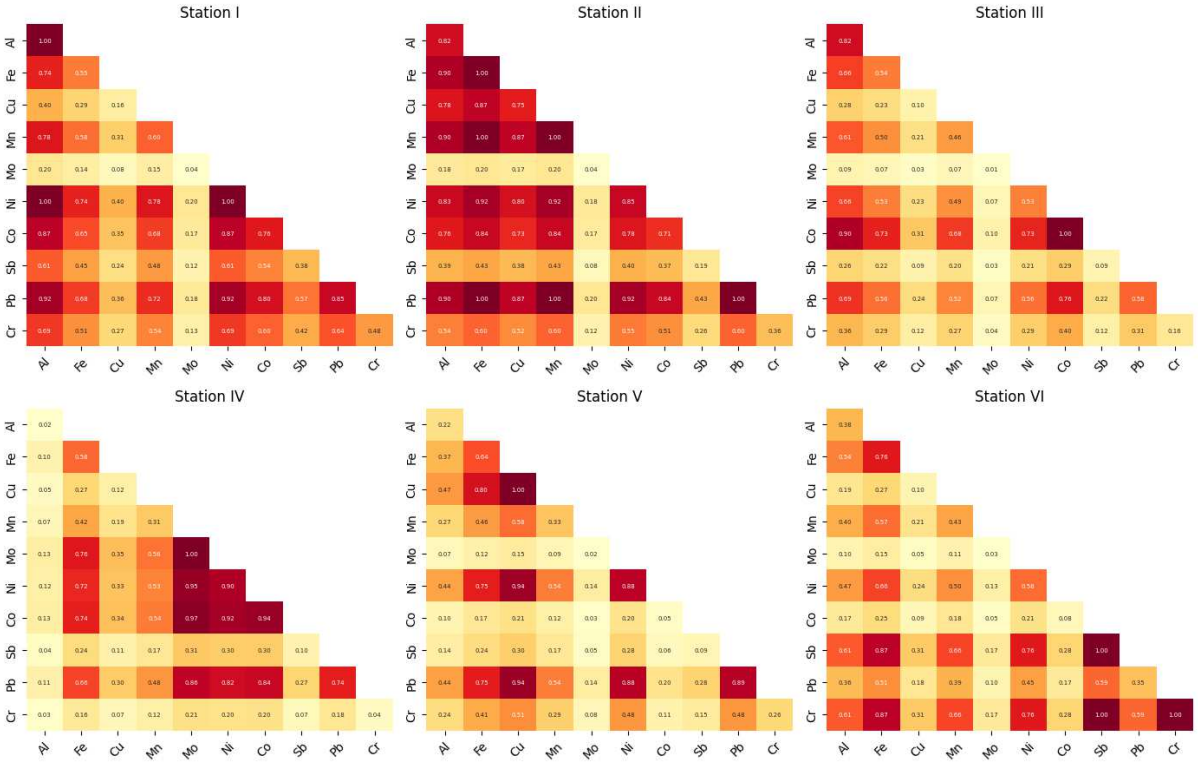



Fig 5. Correlation analysis of heavy metal concentration in the soil samples.

## 3.3. Heavy Metal Pollution in Mazari palm trees

Transfer factor (TF) of heavy metals from soil to Mazari palm tree leaves is depicted in Table 3. TF is a ratio of the concentration of heavy metals in plants to the concentration of heavy metals in soil. Various plant species

accumulate heavy metals to varying degrees. When the growing takes place on the same type of soil, the heavy metal accumulation in different species increases in the following order: grains < root vegetables < fruit vegetables < leaf vegetables(Mastoi, Yang, Deng, Kashani, & Hakro, 2020). The transfer factor is used for evaluating the mobility of metals from soil to plants. The palm leaf is a good bio-indicator of heavy metal pollution of the area.

## 3.4. Demographic and Climatic Variability

The study area soil map illustrates the spatial distribution of major soil types in the Makran region of Balochistan, Pakistan. Soil variability is particularly important for the uptake and transfer of metals in the Mazari palm (*Nannorrhops ritchiana*), which naturally grows in the arid environments of the Makran region.

Furthermore, the region is recognised for the widespread natural growth of the Mazari Palm (*Nannorrhops ritchiana*) in its mountainous areas (M. Ali et al., 2020; Bibi et al., 2015). Makran has an arid climate and receives limited rainfall. The soil, which is saline like much of the region, poses challenges for agriculture (Akhtar et al., 2021). Previous geomorphological assessments have reported spatial variations in tectonic activity from the northern to southern parts of the region, which significantly affect the topography and morphological features of the area (Partabian, Nourbakhsh, & Ameri, 2016).

Long-term temperature records (2000–2025) were analysed to evaluate climatic trends, while corresponding rainfall data were extracted from the same platform to assess precipitation patterns within the study region.

The average rainfall values for each station show significant variation ($P < 0.05$), but the rainfall range is generally low across all stations. Stations III, IV, and V experience average higher temperature and lower precipitation compared to the stations I, II, and VI. These patterns are highly associated with the transfer of heavy metals in water, soil, and mazari palm tree. Fig 6 shows the correlation of temperature and rainfall for six stations selected.

## 3.5 Rainfall trends

The average rainfall values for each station show significant variation ($P < 0.05$), but the rainfall range is generally low across all stations. Values increased from 1985 to 1995, decreased markedly in 2000, and then increased again in 2010 and 2020, followed by a reduction in 2022. The highest rainfall values were recorded at site S-VI, while the lowest values were observed at site S-I

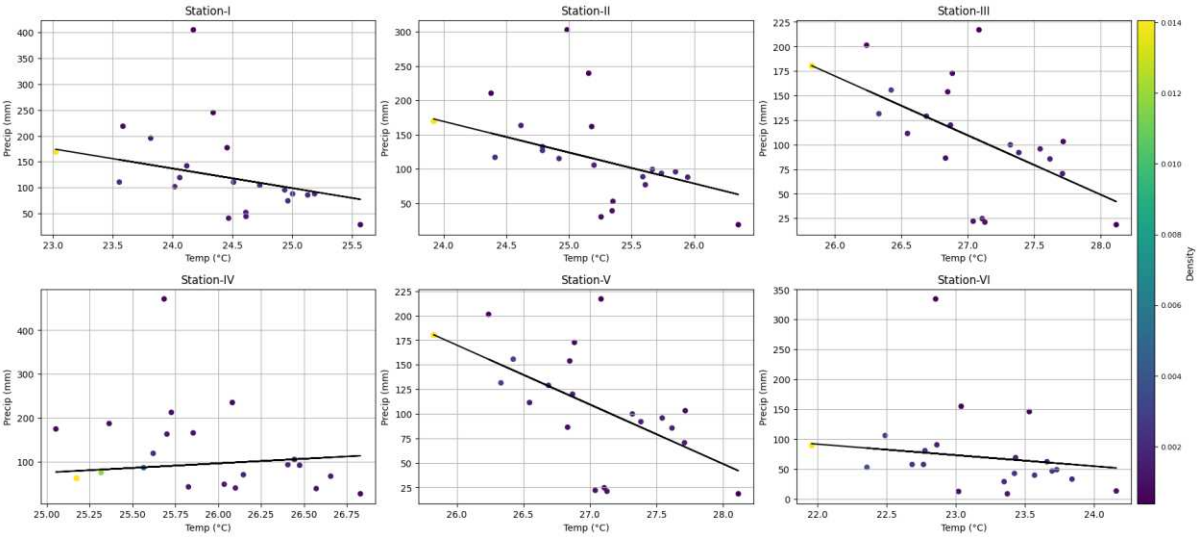
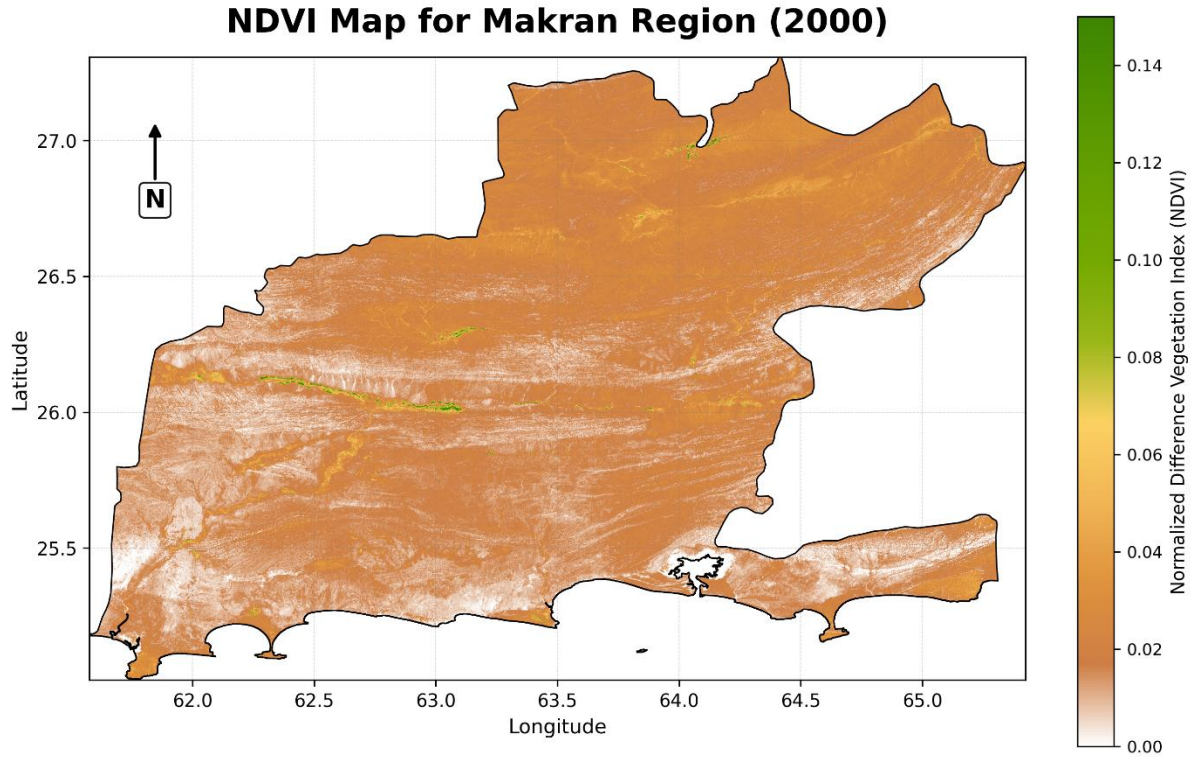


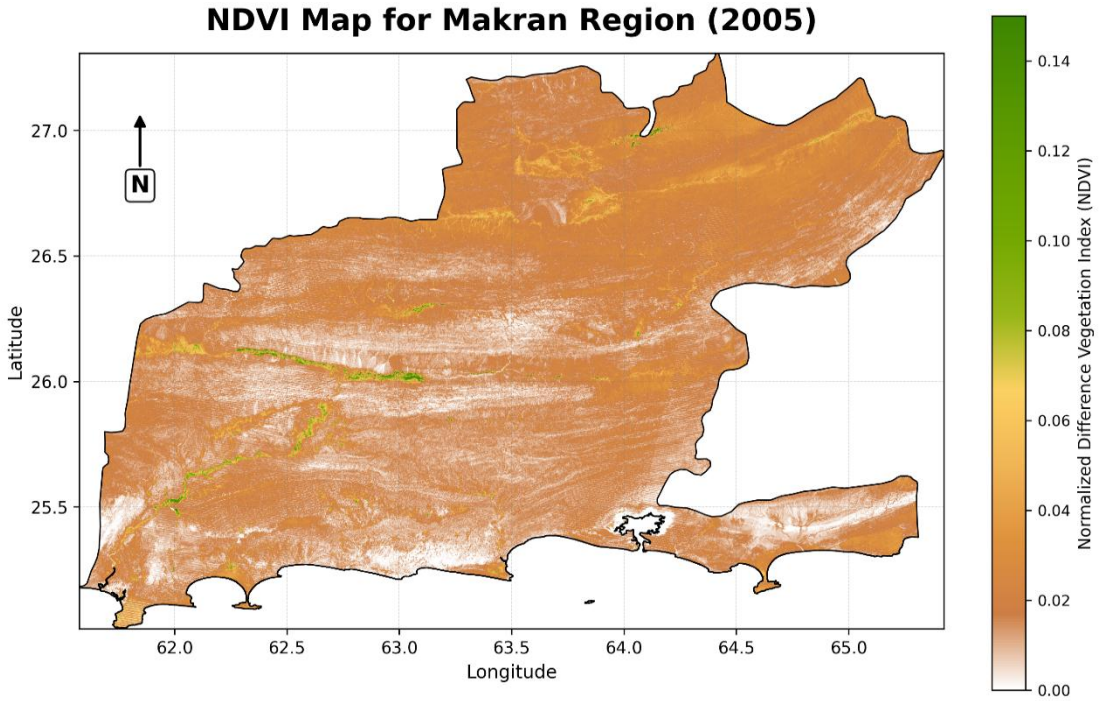

Fig 6. Temperature and precipitation correlation analysis for six stations

## 3.5. Normalised Difference Vegetation Index (NDVI)

In the present study, we prepared an NDVI Map for the vegetation ecosystem health assessment period of 2000–2025 for our study area. This map presents a spatial representation of vegetation health across a designated study area (Figure 6). The colour gradient likely corresponds to NDVI values, a satellite-derived metric employed to assess vegetation health and biomass (Zeng et al., 2022). The NDVI map offers valuable insights into the overall spatial patterns of vegetation health within the study (Fig 7. (a), (b), (c), and (d)).



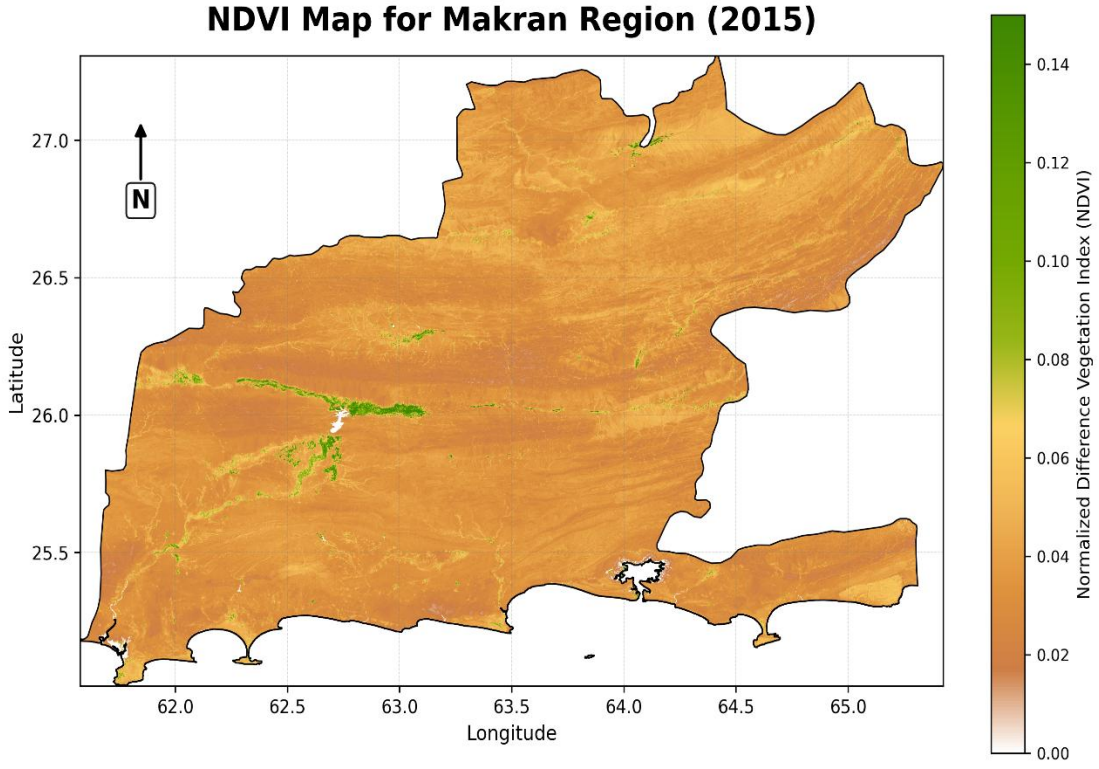
241 Fig 7. (a)




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243 Fig 7. (b)

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246 Fig 7. (c)

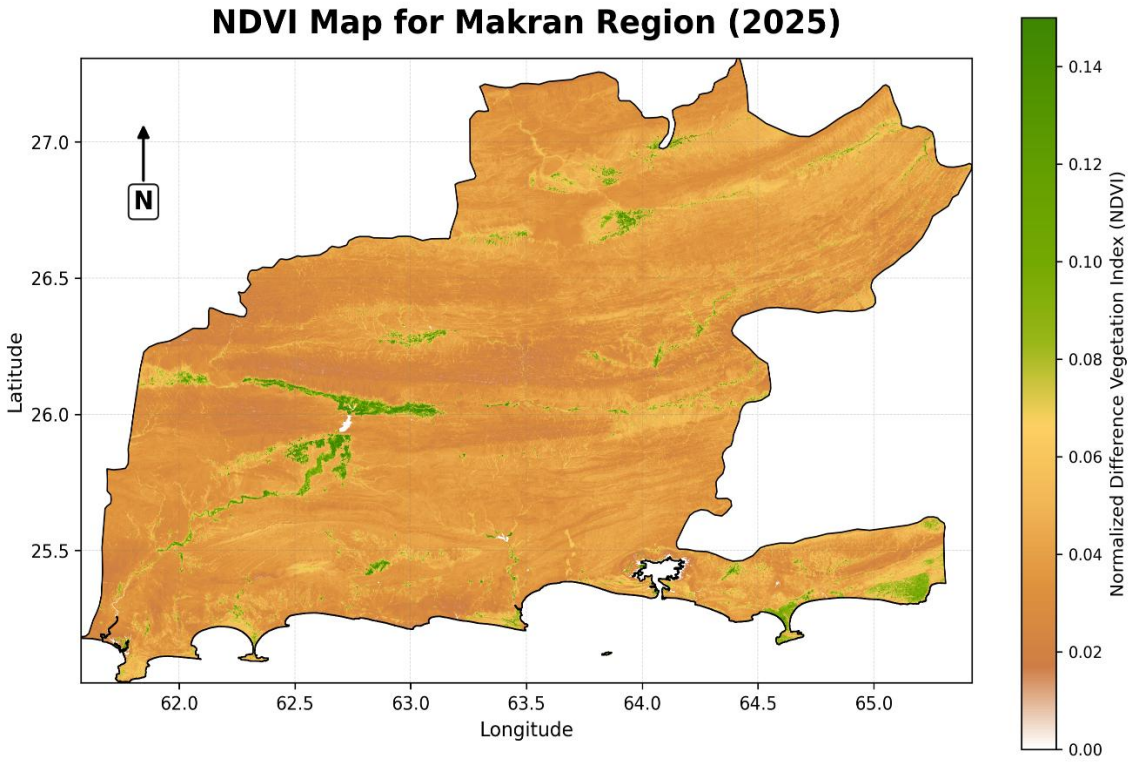



Fig 7. (d). Spatial distribution of NDVI values in the study area (a) 2000, (b) 2005, (c) 2015 and (d) 2025.

## 4. Discussion

Heavy metal pollution in soil, water, and vegetation represents a critical environmental challenge, particularly in arid and mountainous regions. Temperature and rainfall rates are important contributors to heavy metal pollution (Wimalawansa, 2016; Xiao et al., 2024; W. Xu, Jin, & Zeng, 2024). Heavy metals in the Earth's crust, in mountain rocks, and in minerals enter into water bodies during higher temperature.

Studies also reported that in the Makran region, heavy metal contamination is widespread, with Fe, Mn, Pb, Ni, and Cr frequently exceeding WHO limits. Makran water is more severely polluted overall compared to mountain areas, with higher cumulative HPI values. The concentrations of Pb, Cd, and Cr in water samples from Toke District, Kalat, exceed the permissible limits recommended by the World Health Organization, indicating the presence of contamination in the studied water sources. Zn, Mn, and Fe indicating comparatively lower levels. The variation in heavy metal concentration levels highlights the distribution of concentration within the water (Meer et al., 2020). The water samples from Jhal Magsi District, Balochistan exceeded WHO limits for Fe, Cr, and Pb elements. Ni slightly exceeded limits. Cu and Zn remained within permissible limits and indicated lower levels of contamination (Mustafa et al., 2017). The samples from districts Toke (Kalat) and Jhal Magsi demonstrate a consistent pattern in which toxic metals, particularly Pb, Cd, and Cr, exceeded acceptable limits for drinking water, while Cu and Zn remained within acceptable limits. Pb and Mn concentrations exceeded the WHO permissible limits in the Zhob District (Chandio, Khan, Muhammad, Yalcinkaya, & Kayis, 2020). Trace metal analysis of water in Quetta confirms the occurrence of contamination. The presence of As, Cr, Ni, and Cd indicates the release of heavy metal elements from natural mineral sources and anthropogenic activities, including urbanization and subsurface geological interactions.

Water Quality Index (WQI) classifications indicated excellent and medium water quality for samples, even though regional samples exhibited reduced quality, showing spatial heterogeneity in geochemical and environmental controls (Dippong, Hoaghia, & Senila, 2022). Surbakti, 2021 et al. observed HPI values of 130 during the wet season and 143 during the dry season in Bojonegara Coastal Waters, Banten Bay. Metal contamination in aquatic ecosystems must be determined to prevent by the identification of dynamics of climate (Nin, 2021). On the other hand, rainwater runoff transport heavy metals from terrestrial sources into aquatic environments and thereby increases ecological and public health risks (Visser, Kroes, Vliet, Blenkinsop, & Broers, 2011). The study of River Tano revealed clear variability in heavy metal concentrations across water and sediment sources. Higher concentrations of Hg, Cd, Zn, Pb, As, Cu, and Cr were generally observed during the rainy season compared to the dry season in both water and sediments, except for Pb and Cd in sediments, which showed higher accumulation during the dry period (Nyantakyi, Akoto, & Fei-Baffoe, 2019).

The heavy metals in soil, water, and trees highlight the complex pathways of environmental contamination. The Heavy Metals Pollution Index is a vital tool, determining pollution levels, where exceeding heavy metal values indicate pollution (Kashefighasemabadi, Karbassi, Tabatabaee, & Dehabadi, 2019; Ntzala et al., 2013) . Conversely, the Geo-accumulation Index (Igeo) is used to assess soil contamination, categorising soils into various types of pollution. Meanwhile, the transfer factor measures the movement of heavy metals from soil to plants. Values greater than 1 indicating increased transfer of pollutants (Mirecki et al., 2015; Weissmannová & Pavlovský, 2017). The heavy metals pollution index, Geoaccumulation index, and transfer factor were applied to assess pollution levels in water, soil, and Mazar Palm according to the reported approach (Mirecki et al., 2015; Mohan, Nithila, & Reddy, 1996; Ogbeibu, Omoigberale, Ezenwa, Eziza, & Igwe, 2014; Singh, Garg, Gautam, & Kumar, 2014) . Integrated assessment of indices with the observed climatic trends strengthens the understanding of dynamics of heavy metals in the study area.

In this research study, the Heavy Metal Pollution Index (HPI) was calculated for seasonal river water samples from the mountain region, indicating higher contamination values for all six stations. Based on their HPI rankings, Stations III, IV, and V show a significant level of heavy metal pollution. The HPI values ranged 1794.81, 1724.45 1321.60 for stations III, IV, and V, respectively, demonstrating notable spatial variation in pollution levels. Among the analysed metals, these stations exhibit higher concentration of Zn, Fe, Ni, Mn, and Mo significantly contribute to heavy metal pollution at certain stations. Even higher concentration of Zn, Mo, and Mn were analysed at station I, II, and VI; however, the most significant element was Fe at station III, IV, and V. These findings highlight the urgent need for monitoring and climate-aware water management to protect public health.

The higher concentration of HPI for stations III, IV, and V probably associated with the demography and climate patterns of the region. These stations experience average higher temperature and lower precipitation compared to the stations I, II, and VI. The transfer of heavy metal in water source also caused by changing NDVI patterns. Stations III, IV, and V experience change in NDVI patterns in surroundings, which also cause higher concentrations of heavy metals.

Soil is a vital environmental component prone to contamination by heavy metals (Abdu, Abdullahi, & Abdulkadir, 2017). Heavy metal contamination observed in aquatic systems and soil environments also exhibit significant accumulation patterns, as revealed through geo-accumulation index (Igeo) assessment in the present study. Pb, Cd, Cu, and Zn were observed in higher concentrations in geo-accumulation (Patel et al., 2018).

The (Igeo) analysis of soil samples from six distinct Mazari Palm (*Nannorrhops ritchiana*) habitats showed significant pollution. The geo-accumulation index (Igeo) analysis revealed a clear pollution hierarchy in the soils of the study area: Cu ≈, Cr ≈, Zn > Co > Sb > Ni > Mo > Mn ≈ Fe. Among these, Cu, Cr, and Zn are classified as extremely polluted, while Co and Sb range from moderately to extremely polluted, Ni consistently shows heavy pollution, Mo ranges from moderate to heavy pollution, and Mn and Fe remain unpolluted. The most contaminated elements in the soil are Cu, Cr, and Zn. (EDX) analysis identified heavy metals, with Sb (2.66 wt %) being the most abundant toxic element, followed by Mo (0.55 wt.%), Zn (0.54 wt.%), Co (0.49 wt.%), and Cu (0.47 wt.%). Trace amounts of Ni (0.15 wt.%), Mn (0.13 wt.%), and Cr (0.06 wt.%) were also observed (Fig.8). ICP OES confirmed these metals, providing accurate quantitative data that supported the semi-quantitative EDX results. The consistent results of both methods suggest that the heavy metals originate from geological sources.

Similarly, investigations on soil sealing in urban environments have demonstrated notable impacts on heavy metal distribution in Ekranic Technosols, affecting elements such as Cd, Cr, Cu, Hg, Fe, Ni, Pb, and Zn. Using indices such as the Geo-accumulation Index (Igeo), Enrichment Factor (EF), and Pollution Load Index (PLI), these studies have quantified the degree of contamination and distinguished between natural geogenic contributions and anthropogenic inputs. The findings indicate that although soil sealing may only slightly alter overall metal concentrations, sealed soils tend to exhibit higher pollutant accumulation, as reflected by elevated PLI, Igeo, and EF values (Li et al., 2024).

TF decreases when plants grow in heavily polluted soil. In the same soil type, heavy metal accumulation in plants decreases in this order: grains < root vegetables < fruit vegetables < leafy vegetables (Li et al., 2024). In terrestrial systems, plants mainly absorb heavy metals from the soil through their roots. In aquatic systems, the entire plant body can be subjected to heavy metals and ions(Uddin, Zakeel, Zavahir, Marikar, & Jahan, 2021). Similar research has demonstrated that heavy metals show distinct transport patterns and accumulation in mountain soils (Salim, Khan, & Malik, 2020). Other studies were also carried out in Balochistan found elevated levels of heavy metals in soil and vegetation of the ultramafic complex (Ophiolites) and in sedimentary rocks in the Zhob and Loralai valleys of Balochistan. The results showed that these sites contained much higher levels of heavy metals than the reference sites. Effective accumulators were found to be *Phoenix dactylifera L*. and *Calotropis procera L*., the main geogenic source of the pollution. The study suggests employing these plants as bio-indicators and in phytoremediation procedures (Ullah & Muhammad, 2020).

Studies on date palms in Saudi Arabia and Tunisia found that while fruits may accumulate Pb, Cd, and Ni, leaves generally show limited transfer, except for essential elements like Mn and Mo. (Al-Khashman, Ala'a, & Ibrahim, 2011) investigated date palm (*Phoenix dactylifera L*.) leaves as bio-monitors of atmospheric metal pollution in arid and semi-arid environments, supporting the findings of research. The transfer factor (TF) results for Mazari palm leaves indicate poor accumulation of heavy metals, such as Al, Fe, Cu, Cr, Ni, and Co, exhibiting negligible transfer (TF < 0.001). While, Mo showed higher TF values (2.68–7.00. Sb also showed TFs (0.017–0.216), whereas Pb demonstrated moderate uptake (0.021–0.143), with values varying across stations. Mn exhibited moderate TF values (0.023–0.076), aligning with its role as a micronutrient. In addition to these major constituents, several heavy metals were detected at trace-to-minor concentrations, highlighting the plant's role in environmental metal accumulation. Among the toxic elements, molybdenum (1.09 wt.%) and lead (0.65 wt.%) were the most prominent, followed by antimony (0.25 wt.%), zinc (0.21 wt.%), copper (0.15 wt.%), and cobalt (0.07 wt.%). Trace levels of nickel (0.06 wt.%), manganese (0.06 wt.%), and chromium (0.04 wt.%) were also

observed. The detection of these metals in leaf tissues indicates uptake from the surrounding soil and atmosphere, reflecting the geochemical background of the arid-to-semiarid mountainous environment where the Mazari palm thrives. These findings highlight the need for integrated environmental monitoring and mitigation strategies to protect ecosystem stability and sustainability in this arid region.

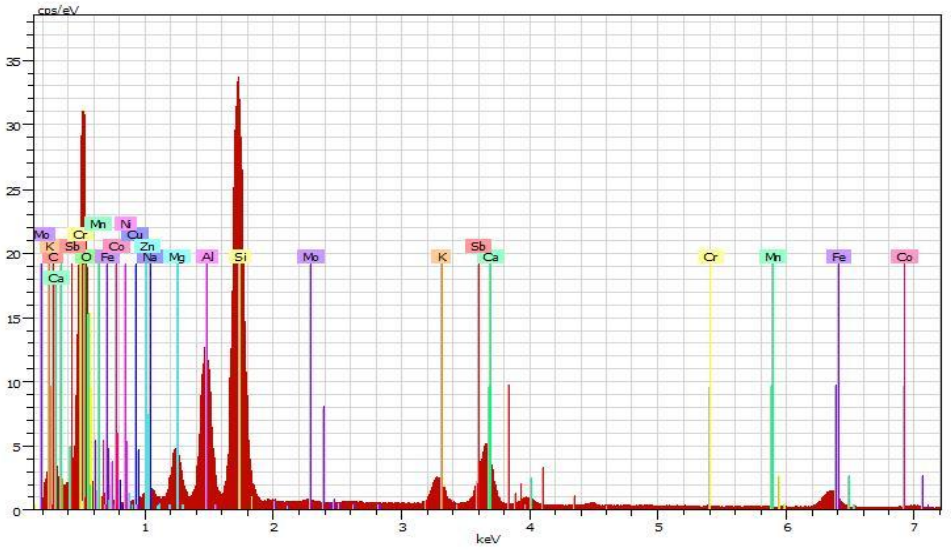



Fig 8. X-ray (EDX) spectrum analysis of heavy metal in the soil sample.

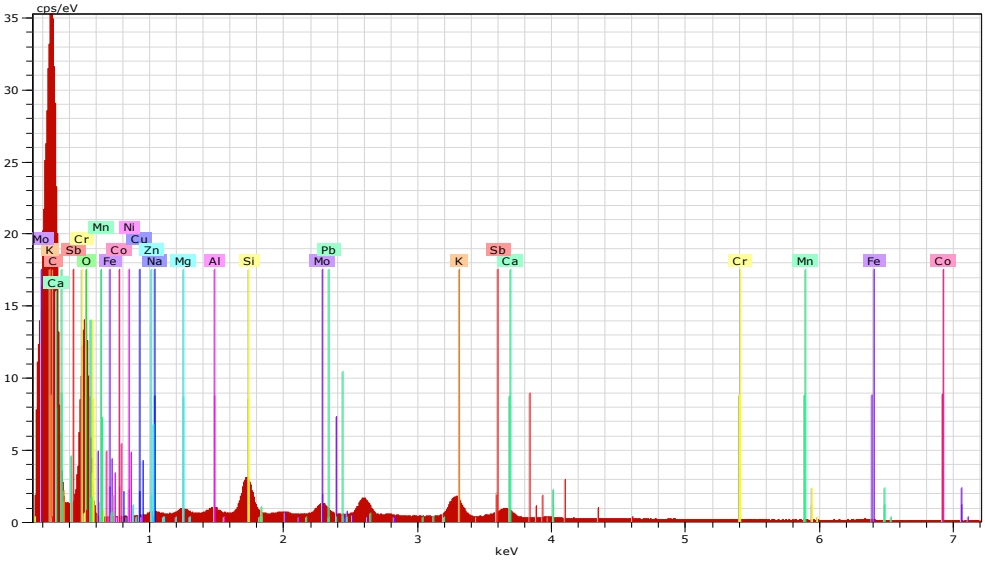



Fig 9. X-ray (EDX) spectrum analysis of heavy metal in the leaf powder sample.

## 5. Conclusion

This study revealed significant heavy metal pollution in water, soil, and Mazari Palm trees and its impact on the vegetation within the Makran Division of Balochistan. These findings suggest a strong relationship between level of heavy metal and the region's high temperatures and low rainfall, and are potentially linked to global warming.

Based on the HPI values, Zn, Ni, and Mo are the main contributors, with Fe, Pb, and Al also contributing significantly, indicating marked spatial variability in contamination. igeo indicated high concentrations and varying degrees of pollution from Cu ≈ , Cr ≈ , Zn > Co > Sb > Ni > Mo > Mn ≈ , and Fe. Among these, Cu, Cr, and Zn are classified as extremely polluted (Class 6), while Co and Sb range from moderately to extremely polluted (Class 3–5). Nickel is consistently heavily polluted (Class 4), molybdenum is moderately to heavily polluted (Class 3), and manganese and iron remain unpolluted (Class 0). EDX analysis of soil identified Sb being the most abundant toxic element, followed by Mo , Zn , Co ,Cu , Ni , Mn , and Cr .

Mazari palm leaves showed negligible transfer of most heavy metals but exhibited exceptionally high Mo uptake (TF 2.68–7.00), along with moderate Pb and Mn accumulation, confirming its role as a bio-indicator of metal mobility in arid soils. The EDX spectra confirmed the presence of molybdenum (Mo) in relatively higher abundance in the leaf tissues of Mazari palm(*Nannorrhops ritchiana)*.

NDVI result shows that Makran is experiencing continuous and severe vegetation loss. These findings highlight the need to implement targeted mitigation strategies to protect the region's ecological balance and public health. Further research is necessary to establish clear causal links between heavy metal accumulation and global warming, which is vital for making informed decisions and striving for a cleaner environment for future generations.

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## Author's contribution

Zafar Ali collected plant, soil, and water samples from study areas and prepared samples for mineral analysis, writing and reviewing the original draft. Farah Naz Talpur designed the study supervised Zafar Ali for experimental work, and checked the final draft of the manuscript; Hassan Imran Afridi contributed for study plan and layout as well as for manuscript preparation, Habibullah Abbasi contributed in plant and geological data collection. Shahjahan Shabbir Ahmed facilitated in the collection of river water samples and some of its analysis

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**Data Availability and Materials:** Data will be made available on request by contacting the corresponding author.

**Ethics, Consent to Participate:** The voucher specimen is deposited in the National Herbarium of Pakistan, Pakistan Agricultural Research Council (PARC), Islamabad, under accession number RAW 102915. The specimen was identified by Amir Sultan on 21 September 2023.

*Nannorrhops ritchiana* (Mazari palm) plant material was collected following local and national guidelines. The plant material was collected responsibly and did not harm protected areas or endangered plant populations. No specific collection permit or licence was required for the plant sample collection in this study.

**Consent to Publish:** Not applicable.

**Permissions to Collect Plant Material:** *Nannorrhops ritchiana* (Mazari palm) samples were collected for scientific research, and no specific permit or licence was required for the collection of the plant material.

**Competing Interest**: The authors declare no competing interests.

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