Research Square

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Multivariate Analysis of Heavy Metal Pollution and Salinity Interactions in Saline Soils for Agricultural Management

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Abstract

This study examined heavy metal (HMs) pollution in saline soils of Sukkur Sindh, Pakistan, and determined the relationship between salinity and metal content. Multivariate statistical methods such as regression analysis, principal component analysis (PCA), and cluster analysis (CA) were applied to characterize anthropogenic and natural factors affecting HMs in soils. Close relationships were found for electrical conductivity (EC) and cadmium (Cd), cobalt (Co), chromium (Cr), copper (Cu), lead (Pb), and zinc (Zn) concentrations, but correlation strength differed among soil samples. Bulk Saline Soil (BSS) samples had Cd (1.01–3.62 µg/g), Co (18.6–29.1 µg/g), Cr (5.07–13.6 µg/g), Cu (122–191 µg/g), Pb (4.01–9.99 µg/g), and Zn (170–193 µg/g). Regression analysis was also used to demonstrate the need for EC as well as the measurement of HMs concentration in agricultural management. PCA indicated that variables under PC2 were generally orthogonal to PC1, with a third factor (PC3) accounting for 19.7% data variance, demonstrating the presence of other independent factors influencing HMs accumulation aside from the main components described. The results emphasize the significance of integrated EC and HMs monitoring in successful salt-affected farmland management.

Introduction

Salt occurs naturally in water and soil. However, when there is too much salt, the soil is described as saline, meaning that the soil does not meet our economic, aesthetic, and environmental needs. This needs to be solved for our landscapes and ecosystems to be productive and healthy (Waris et al., 2023). Solution to such issues are crucial for the environmental well-being of the area and sustainable agriculture (JAMPASRI & SAENG-NGAM, 2019). Soil salinization threatens the biochemical, hydrologic, and erosion processes that favor Earth's environments and natural biological procedures that are indispensable for life. Multiple studies demonstrate that heavy metals like Cd, Cr, and Pb contaminate soil, water, and air through both natural and anthropogenic sources. Their toxicity depends on exposure dose, route, and individual factors like age and genetics (Hassan et al., 2024; Ishak et al., 2025). Severe health consequences including neurological disorders, developmental delays, and increased cancer risks. specifically highlights molecular toxicity mechanisms like DNA damage, oxidative stress, and disrupted cellular processes (Ogwu et al., 2025). The evidence is robust, with studies spanning terrestrial and aquatic organisms showing consistent oxidative stress mechanisms. Over a dozen environmental pollutants capable of ROS overproduction, including ozone, nitrogen oxides, particulate matter, and pesticides. Critically, the oxidative stress potential varies by pollutant type and concentration, with ultrafine particles and transition metals being particularly potent (Ahandani et al., 2022; Talas et al., 2008).

The most salinized soils are found in several Central and Western Asian nations, such as Pakistan, China, America, India, Argentina, Sudan (Kumar & Sharma, 2020; Tahir & Khaliq, 2018). To maintain the agricultural legacy and ensure food security, this trend demands utmost attention (Ayangbenro & Babalola, 2017; Chaoua et al., 2019). Low-quality groundwater is used for irrigation because there is a lack of high-quality water sources. One of the main ways that saltwater enters the Indus Basin and

causes issues with salt and water salinization is through the overuse of such low-quality groundwater (Caglar et al., 2019; Qureshi et al., 2008). Salinity is another crucial factor that affects metal toxicity, mobility, and transport. According to research, HMs have a high level of environmental resistance and may bioaccumulate over time. The chemical characteristics, concentration, and soil availability largely define toxic metal toxicity and mobility of toxic metals. Compared to higher salinity, the biologic impact of HMs is much greater at low salinity (Bai JunHong et al., 2019). The mobility and toxicity of HMs in soils depend on their chemical characteristics, concentration, and availability. Lower salinity levels can have a more significant biological impact on HMs (Bai JunHong et al., 2019). Soil contamination with HMs is exacerbated using wastewater, pesticides, fertilizers, and improper disposal of industrial and urban waste. Addressing these sources is critical for environmental protection and public health (Waris et al., 2022). The global issue of HMs contamination in saline soils, particularly concerning metals such as Cd, Co, Cr, Cu, Pb, and Zn, poses a serious ecological challenge (Bartkowiak et al., 2017). Multivariate statistical analysis is essential for understanding and managing soil contamination, facilitating the efficient processing of data to uncover patterns and relationships. Techniques such as PCA and regression analysis have proven effective in revealing the underlying trends and complex correlations in environmental data (Baig et al., 2010; Chudasama et al., 2024).

This study aimed to analyze HMs concentrations in saline soils from four sites in Sukkur, Sindh, Pakistan. By employing multivariate analysis, we can differentiate between anthropogenic and natural sources of HMs pollution, providing crucial information for targeted remediation efforts and enhancing environmental health.

Materials and methods

Sampling of BSS

To obtain spatial variation, a stratified random sampling technique resulted in a total of 200 saline soil samples from four Sukkur sites (50 samples each). Following surface debris removal, samples were collected from the 0–15 cm soil layer using a stainless-steel auger. Clean, identified plastic bags held each sample (~ 500–1000 g). Triplicate and blank samples were included for quality control, and equipment was washed between collections. Before physico-chemical analysis, air-dried and sieved (2 mm) all samples were cooled and transported to the laboratory.

Chemical reagents and glassware

Deionized water was obtained using a purification system (Bedford, MA, USA). Merck (Darmstadt, Germany) purchased analytical-grade hydrogen peroxide and nitric acid. Filter paper (0.45 µm) was purchased from Biotech (Germany). Standard solutions (1,000 mg/L) were diluted to create working standards for Cd, Co, Cr, Pb, Cu, and Zn. The analysis involved the use various equipment, including a

conductivity meter, flame atomic absorption spectrometer (FAAS), and graphite furnace for evaluating HMs.

Physical-chemical evaluations of salty soil

The EC, pH, and organic matter (OM) quality features of each soil sample were evaluated using recognized methods (Waris et al., 2022). A 1:2.5 soil-to-water ratio was used to evaluate characteristics, and a conductivity meter measured EC. The OM content was determined by heating the soil samples in a muffle furnace at 540°C for six hours, with calculations based on weight differences before and after ashing (ASTM, 2007).

Samples preparation procedure HMs in BSS

Soil samples (5 g each) were combined with an acid solution (6 ml HNO_3 and 2 ml H_2O_2) to break down organic material. The mixtures were heated on an electric hot plate for two-three hours. Finally, the digested samples were analyzed using FAAS and graphite furnace atomic absorption spectroscopy (GFAAS).

Chemometric analysis

Multivariate statistical analysis was employed to identify hidden patterns in large datasets that could indicate HMs contamination sources. PCA and cluster analysis were used to differentiate metal sources in soils (Young & Hammer, 2000). Regression analysis was used to evaluate the metal-soil property relationships, and all analysis was conducted using OriginPro statistical software to achieve accuracy (Hou et al., 2017).

Results and discussion

Physico-chemical analysis of BSS

The relationship between soil salinity and HMs mobility remains unclear. The increased mobility of HMs due to salinization is a significant concern that must be considered in environmental risk assessments (Acosta et al., 2011). In addition, OM content is very important for maintaining soil integrity; however, our findings revealed abysmally low rates of between 0.620% and 1.45%. This indicates that the land is not sufficient for agriculture, thus the necessity of taking prompt restoration measures. Soil pollution with HMs is a severe environmental issue owing to the high toxicity and persistence of the pollutants. This problem negatively impacts soil quality, and it is difficult to identify areas with fertile soils (Waris et al., 2023). Several aspects of biological life are threatened by non-biodegradable chemicals and dangerous chemicals that are beyond safety thresholds. Cd concentrations in BSS samples range from 1.11 to 3.71 µg/g, Co concentrations range from 17.8 to 23.9 µg/g, Cr concentrations range from 6.07 to 23.9 µg/g,

Cu concentrations range from 108 to 193 µg/g, Pb concentrations range from 4.33 to 11.1 µg/g, and Zn concentrations range from 118 to 181 µg/g (Table 1). Heavy metal contamination in soils frequently exceeds international safety standards, posing significant risks to crop production and human health. WHO target values for heavy metals follow the order Cr > Pb>Zn > Cu>Cd, with Cd presenting the highest potential risk (target value of 0.8 µg/g. The soils surrounding industrial companies were contaminated with Cd and Pb, exceeding USEPA and European Union standards, while some heavy metal concentrations were within acceptable thresholds, Cd levels consistently exceeded the permissible limit of 3.00 µg/g (Caglar et al., 2019; Tóth et al., 2016; Yang et al., 2018). The occurrence of these HMs in BSS is of considerable concern because they are bioavailable, transportable, and ecotoxic to ecosystems. Thus, the determination of the total concentration of these metals does not entirely indicate environmental pollution, hence the need to conduct additional studies are required (Waris et al., 2021).

Table 1
The concentration of HMs (µg/g) in BSS samples is based on physicochemical parameters.

Parameters		BSS1	BSS2	BSS3	BSS4
pH	Mean ± SD	7.33 ± 0.05	7.78 ± 0.06	7.89 ± 0.11	7.12 ± 0.69
	Range	7.28–7.38	7.72–7.84	7.78-8.00	6.45–7.81
EC (dS/m)	Mean ± SD	4.89 ± 0.44	4.91 ± 0.72	5.11 ± 0.61	5.10 ± 0.62
	Range	4.45–5.33	4.19–5.63	4.50–5.72	4.48–5.72
OM (%)	Mean ± SD	1.67 ± 0.33	0.86 ± 0.13	0.72 ± 0.09	0.97 ± 0.11
	Range	1.34-2.00	0.73–0.99	0.63–0.81	0.86–1.08
Cd	Mean ± SD	1.89 ± 0.29	1.33 ± 0.17	3.71 ± 0.29	1.11 ± 0.17
	Range	1.60–2.18	1.16–1.50	3.42-4.00	0.94–1.28
Co	Mean ± SD	19.3 ± 1.36	23.9 ± 2.31	17.8 ± 2.65	19.9 ± 1.98
	Range	18.9–20.7	21.6–26.2	15.2–20.5	17.9–21.9
Cr	Mean ± SD	6.09 ± 1.18	14.9 ± 2.61	9.09 ± 1.76	10.9 ± 1.51
	Range	4.91–7.27	12.3–17.5	7.33–10.9	9.39–12.4
Cu	Mean ± SD	108 ± 4.81	112 ± 5.54	119 ± 4.00	193 ± 5.79
	Range	104–112	106–118	115–123	187–199
Pb	Mean ± SD	4.33 ± 0.93	5.41 ± 0.87	11.1 ± 1.23	9.89 ± 1.23
	Range	3.40–5.26	4.54–6.28	9.87–12.3	8.66–11.1
Zn	Mean ± SD	133 ± 4.56	118 ± 4.11	119 ± 3.09	181 ± 4.19
	Range	128–138	114–122	116–122	177–185

Principal Component Analysis

PCA was used to investigate the concentrations of HMs in BSS, revealing their presence and spatial distribution. These data are crucial for assessing potential risks and formulating management strategies in contaminated regions (Deljomanesh et al., 2024). Additionally, PCA is a useful tool for assessing how human activity affects river water quality, emphasizing the need to use a variety of approaches to pinpoint HMs sources in river basin regions areas (Ogwu et al., 2025).

In this study, a dataset of physicochemical parameters and HMs content dataset from different soil samples was subjected to PCA. This was performed to decrease the number of descriptors that may be responsible for the total variance in the experimental data. Independent analyses were performed on

normalised datasets of BSS with nine variables for four different sampling locations (n = 24) (Table 2). The largest variances in the data were accounted for by the first principal component (PC1), 53% explained. PC1 in most datasets can be used to define an overall trend or prevailing factor, such as a contamination zone or fertility gradient, according to data context. The second principal component (PC2) accounted for a further 27.4% unexplained variability by PC1. Values closer to PC2 than to PC1 indicate a trend or pattern in development, presumably of a different factor than that accounted for by PC1. A further 19.7% of the unexplained variability that neither PC1 nor PC2 could explain was described by the third main component, PC3. A secondary gradient, such as industrial pollution, is created when variables that point with long arrows on the PC3 axis contribute significantly to this third axis of variation and may indicate a common source or type of behavior in the soil (Fig. 1).

Table 2
Loadings of experimental variables (36) on key principle components for BSS samples.

Variables	**PC 1**	**PC 2**	**PC 3**
pH	0.410	-0.213	-0.009
EC (dS/m)	0.299	0.430	0.121
OM %	-0.401	-0.250	0.230
Cd (µg/g)	0.90	0.370	0.607
Co (µg/g)	0.234	-0.118	0.080
Cr (µg/g)	0.250	0.110	-0.580
Cu (µg/g)	-0.027	-0.490	0.420
Pb (µg/g)	0.409	-0.021	0.233
Zn (µg/g)	-0.152	0.550	0.200
Eigenvalue	5.208	2.740	2.000
Total variance %	54.0	28.4	20.0
Cumulative %	54.0	81.0	100

The first principal component, the X-axis (PC1), explained 48.32% of the overall variation in the data. The second principal component, which explained 33.68% of the variation, was the Y-axis (PC2). 82% of the data variance may be explained by these two factors (Fig. 1). This pattern is observed in cases effected by industrial processes, mining, or agricultural runoff, ehre the same forces affect all three readings. EC within a system is most often affected by dissolved salts, nutrients like nitrogen, and HMs (Ogwu et al., 2025). The correlation values in the matrix indicate that soils with high EC values are likely to have greater dissolved concentration of metals and nutrients, and EC can thus be used as an indicator of soil contamination or fertility. High pH levels precipitate Cu compounds or enhance their adsorption by soil

particles. These modifications can decrease the mobility and bioavailability of Cu but can sustain a higher total soil concentration (Rees et al., 2014). Salinity can affect both the chemical speciation and pH of Cu. The presence of salt in the soil can influence the activity of Cu ions, which could result in a situation where an elevated pH corresponds to enhanced Cu retention (Wu et al., 2022).

Cluster analysis (CA) was applied to a database of HMs composition and EC for the four saline soil sampling points. The objective was to identify spatial differences and similarities among these sites (Fig. 2). HMs such as Cd, Cr, Cu, Pb, and Zn may occur in various oxidation states and interact with soil constituents. The strong binding of EC to Cd and Pb implies a probable correlation (Khan et al., 2024). This is evidence to prove the fact that regions with high EC also exhibit high concentrations of HMs due to human interventions or natural chemical weathering (Ali et al., 2019). The findings would indicate a relationship between HMs pollution and EC, and probable implication of industrial effluent or dissolved salt (Mokarram et al., 2020).

Regression analysis of physicochemical properties and HMs BSS

Regression analysis was applied to measure the direction and magnitude of the linear relationship between two continuous variables. In the present study, it was used to determine whether changes in soil EC influence HMs release. An interesting effect of an increase in EC on mobilization of HMs was indicated (see Table 3). The most dramatic and statistically significant alterations were found in the mobilizing of Cd, Co, and Cr in BSS1 and BSS2. An increase in EC was associated with a much higher release of Cd than of other metals. Cd and Cr were the most mobile, implying that they are more displaced by salts or are more likely to react with chloride than the other metals (Tangahu et al., 2011). The % of Zn released showed a minor increase with rising EC, but this was less pronounced than the changes observed of Cd and Cr. These actions can be explained by the chemical interactions between soil particles and by salinity effects. These interactions will regulate in large measure the mobility and bioavailability of these metals in the environment. Therefore, these elements will have minimal mobility and leaching potential, and their relative stability in the soil (Porter et al., 2004).

Table 3
Regression Analysis of HMs and EC in BSS

	BSS1	BSS2	BSS3	BSS4
Cd	y = 0.0564x + 1.750 R^2 = 0.929	y = 0.2125x + 0.289 R^2 = 0.913	y = 0.1970x + 2.544 R^2 = 0.223	y = -0.479x + 3.111 R^2 = 0.491
Co	y = 1.265x + 11.90 R^2 = 0.851	y = 1.419x + 13.901 R^2 = 0.400	y = 1.164x + 22.298 R^2 = 0.535	y = 1.496x + 20.580 R^2 = 0.0702
Cr	y = -0.219x + 6.007 R^2 = 0.801	y = -7.271x + 49.675 R^2 = 0.798	y = -3.506x + 25.308 R^2 = 0.178	y = 0.401x + 10.212 R^2 = 0.0131
Cu	y = -12.130x + 239.91 R^2 = 0.105	y = -40.560x + 330.27 R^2 = 0.670	y = 36.793x − 24.901 R^2 = 0.391	y = -20.301x + 287.18 R^2 = 0.178
Pb	y = -0.567x + 7.501 R^2 = 0.0820	y = -0.276x + 5.999 R^2 = 0.021	y = 0.242x + 8.401 R^2 = 0.037	y = 2.011x − 0.0101 R^2 = 0.403
Zn	y = -5.021x + 217.00 R^2 = 0.0450	y = -42.010x + 411.0 R^2 = 0.705	y = 46.401x − 38.111 R^2 = 0.740	y = 32.001x + 27.010 R^2 = 0.307

Heat map correlations study of physicochemical properties and HMs BSS

Heatmaps will facilitate the identification of connections between pollutants and soil chemistry parameters. Finding likely connections or impacts of variables may be aided by strong positive or negative correlations. With an increase in the pH of the soil, Zn solubility in soil declined (Fig. 3) Such a trend is typically observed in the common chemical behaviour of most metals, which have higher solubility in acids and reduced solubility in alkalis. High EC generally reflects the makeup of more soluble ions, such as metals like Cd. Industrial pollution, fertilizer application, and wastewater irrigation can result in high EC along with elevated HMs composition. Cu and Pb generally have the same origins such as industrial effluent, mining, or urban pollution and can co-exist in polluted soils (Sahay et al., 2019). A high positive correlation implies that whenever Cu content is higher, the Pb content will also be higher. Both metals can be carried by the same medium, as there is a common source of contamination, and the same soil conditions may favour their co-occurrence in solution. This type of information facilitates making informed decisions about liming, salinity control (for EC reduction) and mitigation of HMs contamination. Existence of strong correlation between polluters may imply a shared source of pollution with remediation implications (Selvam et al., 2024).

Conclusion

PCA indicated that the first three principal components account for 100% of soil variation, whereas EC has a strong correlation with HMs concentration. CA confirmed the correlation, especially between EC, Cd, and Pb, indicating shared sources or chemical transformation in saline environments. This analysis is interesting, especially with the concerning the third main component (19.7% of residual variation). Heatmaps describe key correlations between metal solubility and soil chemistry parameters and pollutants and demonstrate EC and pH as being important in metal solubility. Salinity controls and chemical reactivity with soil solids governs metal bioavailability, although most metals are relatively immobile with low leaching and substitution affinities. These correlations remediation of metal-polluted saline environments more efficient. Salinity reduction minimizes HMs pollution and promotes workplace health and agricultural productivity. Further studies on these parameters are necessary to ensure soil health.

Declarations

Conflict of Interest

All authors have agreed to the submission to the current study and have no conflict of interest. It is confirmed that the proposed study is not submitted elsewhere for publication. On behalf of all authors, the corresponding author states that there is no conflict of interest. Meanwhile, there are no institutional, venders or public financial of non-financial conflict of interest.

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Consent to Publish

Not applicable. This study does not include any individual person’s data in any form.

Ethics and Consent to Participate

Ethics approval and consent to participate: Not applicable. The study involved physicochemical/analytical experiments only and did not require ethical approval or participant consent.

Author Contribution

Muhammad Waris conceptualized the study, designed the methodology, performed data analysis, and drafted the original manuscript. **Nadir Hussain** comtributed to validation of results and critical revision of the manuscript. **Summan Urooge** contributed to data collection, experimental work. All authors reviewed and approved the final version of the manuscript.

Competing Interests

It is declared that there are no competing interests.

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Figures

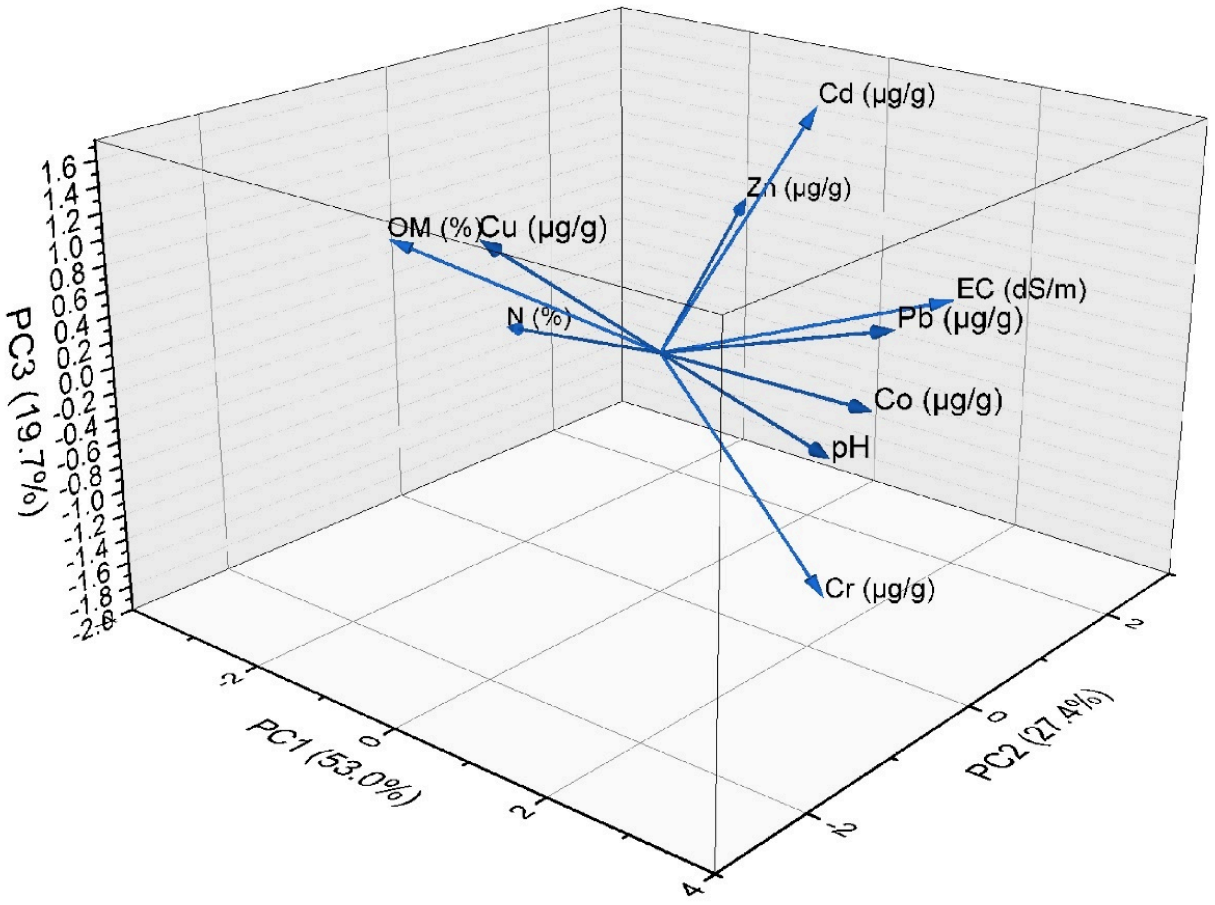


Figure 1

3D loading plot from Principal Component Analysis (PCA) showing the contribution of soil physicochemical parameters and HMs.

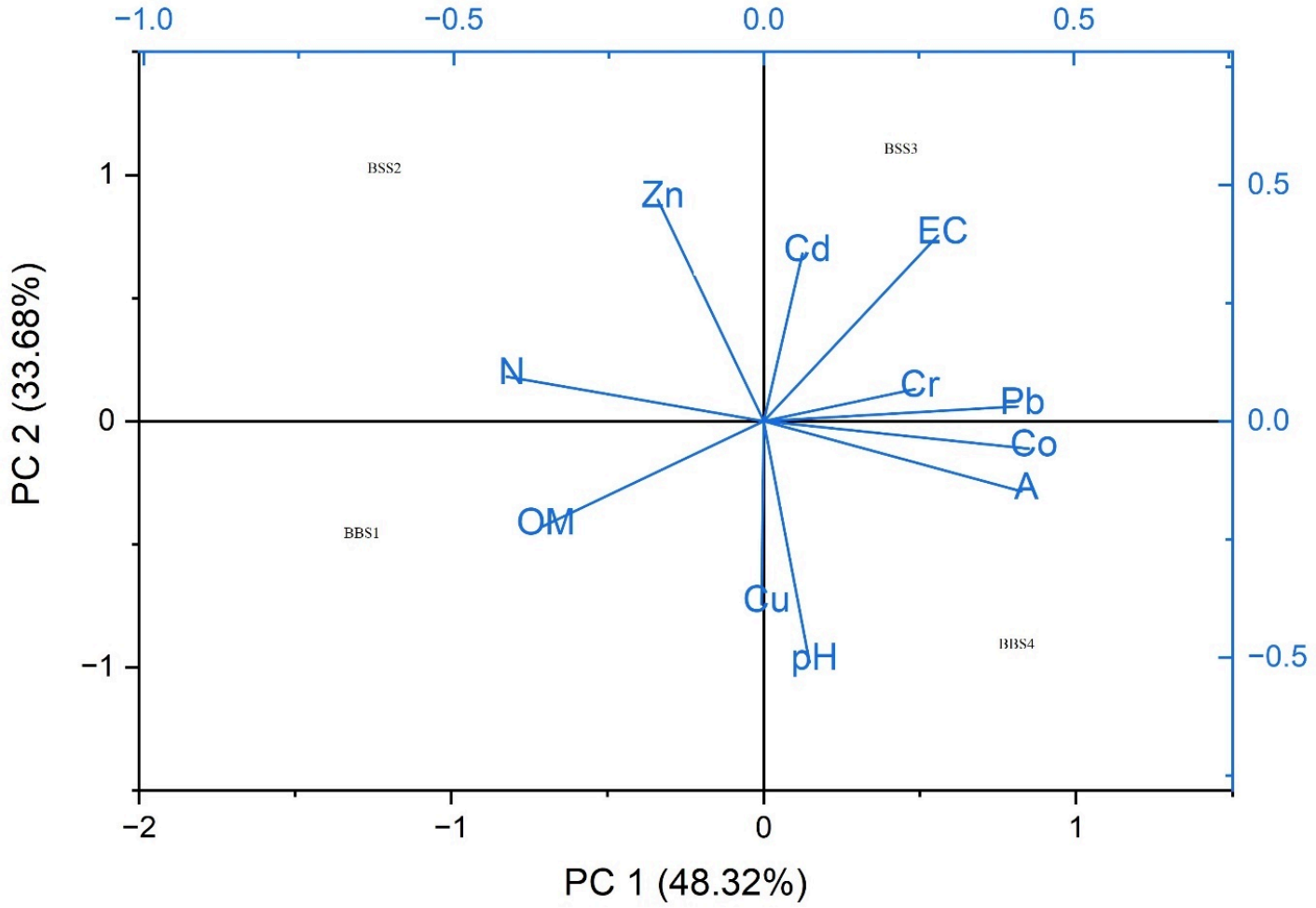


Figure 2

Principal Component Analysis (PCA) biplot showing the relationships between sampling sites and environmental variables.

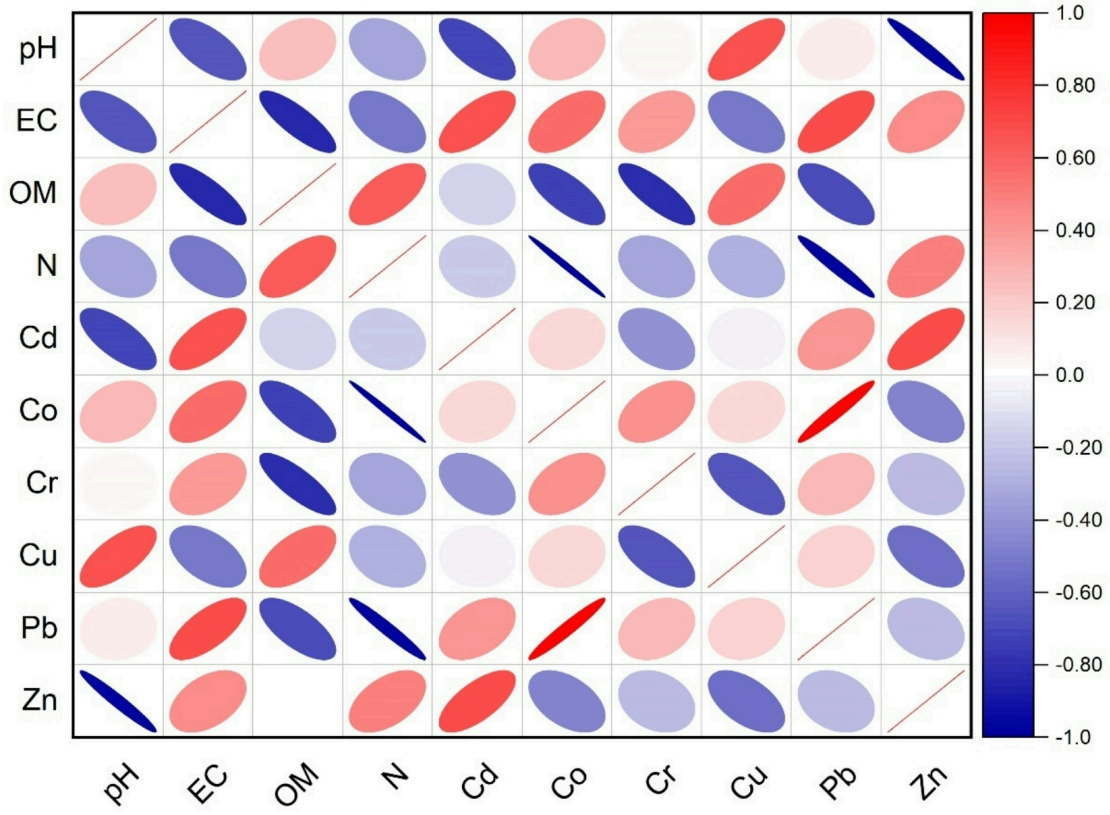


Figure 3

Correlation matrix of soil parameters and HMs