



Science Forum (Journal of Pure and Applied Sciences)



Journal Homepage: <https://atbuscienceforum.com.ng/index.php/jpas>

Applicability of Regression Models for Predicting Manganese and Lead Concentrations in Soils of Bauchi Local Government Area, Nigeria

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Abstract

Heavy metal contamination in soils poses a significant environmental and public health concern, particularly in rapidly urbanizing areas where industrial, agricultural, and domestic activities contribute to elevated trace-metal levels. This study assesses the applicability and performance of regression-based statistical models for predicting the concentrations of manganese (Mn) and lead (Pb) in soils from selected contaminated sites within Bauchi Local Government Area, Nigeria. The overarching aim is to develop empirical relationships that can reliably estimate heavy-metal concentrations from easily measurable soil physico-chemical properties, thereby reducing the need for frequent and costly laboratory analyses. Soil samples were systematically collected from three representative sites at a depth of 30 cm, corresponding to the active root zone and potential contaminant accumulation layer. Laboratory analyses were performed using standard procedures: concentrations of Mn and Pb were quantified using an Atomic Absorption Spectrophotometer (AAS), while pH, electrical conductivity (EC), and moisture content (MC) were measured to characterize the physico-chemical properties of the soils. Descriptive and inferential statistical analyses were employed to evaluate spatial variations and the strength of relationships between metal concentrations and the measured soil parameters. Results revealed spatial heterogeneity in the distribution of Mn and Pb across the study sites, with mean concentrations generally exceeding background values reported for uncontaminated soils in similar geological settings. At a significance level of $P < 0.05$, both Mn and Pb exhibited strong and positive correlations with one or more of the physico-chemical variables. Regression modeling demonstrated that several linear models provided excellent fits to the observed data, with adjusted R^2 values exceeding 0.70, indicating high predictive accuracy and model reliability. The diagnostic tests further confirmed the absence of multicollinearity and heteroscedasticity, validating the robustness of the developed equations. The established regression models are therefore considered suitable tools for rapid and cost-effective prediction of Mn and Pb concentrations in soils of Bauchi and similar environments. These models offer practical advantages over conventional metal-determination techniques by minimizing analytical cost, field effort, and time, while maintaining acceptable precision and reproducibility. Consequently, the approach provides an efficient framework for routine monitoring, environmental assessment, and risk management of heavy-metal contamination in urban and peri-urban soils. The findings further highlight the potential of integrating statistical modeling with geochemical monitoring for sustainable soil-quality management and early-warning systems in developing regions.

Keywords

Linear models,
Lead,
Manganese,
Physico-chemical properties,
Regression

ISSN 1119-4618



1119 4618

JPAS



— Faculty of Science, ATBU Bauchi —

Introduction

The amount of trace metals released into the environment by humans is a source of growing environmental concerns to environmentalists and stakeholders. As the soil metal load in the environment keeps increasing daily from agricultural inputs, industrial, auto-mechanic and other municipal wastes disposal; and their associated leachates release (kanu, *et al.*, 2020; Bi *et al.*, 2020; Soni and Amarnath, 2021, Lui *et al.*, 2022), the quality of soil and its ability to sustain life is seriously compromised.

Soils around waste dumpsites and urban soils are contaminated with trace metals like Cr, Pb, As, Fe, Ni, Zn, Co, Hg, Cd, Mn, Cu (Jiang *et al.*, 2014; Eze, 2015; Soni and Amarnath, 2021; Wu *et al.*, 2021a). These metals have been associated with a lot of illnesses ranging from abdominal issues, cancer, cardiovascular disorders to the central nervous system dysfunction (Palansooriya *et al.*, 2020; Abdullahi *et al.*, 2021; Kumuduni *et al.*, 2022). Elevated levels of this trace metal levels in the soil would definitely result to increased environmental pollution, which will negatively impact not just on the soil, water and air environments but also plants and humans due to due to the continual migration of contaminated dust or leachates into non-contaminated sites (Ogbonna *et al.*, 2009; Jiang *et al.*, 2014).

Monitoring the level of trace metals in the environment has becomes very paramount since the generation and disposal of wastes containing these metals by unsupervised human operations have continued to contaminate the environment. However, the continuous monitoring and assessment of trace metals in

soils is very expensive and rigorous. Developing models to adequate predict these metals have therefore become very imperative. Linear regression models can be used for the purpose of prediction and forecasting. They have been studied rigorously, and used extensively in practical applications because their unknown parameters are easier to fit than models which are non-linearly related to their parameters. The statistical properties of their resulting estimators are also easier to determine (Yan, 2009).

Linear regression models are mathematical models, which uses the least square estimate in order to develop model that can predict data with adequate levels of accuracy. It ensures that the line with the property that the sum of the squares of the errors of the off-line points measured along the Y - axis is least, gives the best fitting line (Abdussalami, 2008). Linear regression has been widely used in both physical, behavioural and social sciences to describe possible relationships between variables. In Korea, its application has been explored to identify the dominant factors influencing metal uptake by plants (Myung, 2008). Regression model was also successfully used for the prediction of extractable fraction of Zn, Cu and Ni using total soil contents of Zn, Cu and Ni (Zdenko *et al.*, 2010).

Lawan *et al.*, (2012) estimated the mobility factor of heavy metal in contaminated soil against native concentrations in dumpsites located in three different districts of Maiduguri metropolis. With well-developed trace metal models as these, immediate steps might be taken to easily monitor contaminated sites regularly in environment. This study is

therefore aimed at developing linear models that would easily predict the level of Pb and Mn in the soil in Bauchi, without undertaking rigorous laboratory exercises.

Methodology

Study Area

The study was carried out in Bauchi State. Yelwa Tudun (Site1), Jos Road (Site2) and Fadamamada (Site3) areas of Bauchi LGA were selected for the purpose of the study due to the volume of human activities and waste dumping in these areas.

Sample Collection and Preparation

Stratified random sampling technique was used in this study for each of the site to be investigated. Ten strata were identified in each of the selected sites. At least 600 soil samples were collected at a depth of 0 - 30 cm in those subsections (strata) by simple random sampling. 20 soil samples collected per strata in each site were homogenized to form ten composite samples for each contaminated site so as obtain sufficient information on soil characteristics for each section of the sites separately (Gomez and Gomez, 1984; Atulegwu *et al.*, 2013). Soil samples were air dried for one week in a well-ventilated space. They were sieved through 2 mm mesh to prevent chemical microbial changes and to remove large mineral inclusions and organic debris. The sieved samples were stored in labelled polythene bags and used for subsequent analysis (Okeke *et al.* 2014).

Sample Digestion

Dried soil samples were pulverised, after which 2.0g of each of these samples was then digested with 20 cm³ aqua regia ((HNO₃: HCl, 3:1 ratio) following standard procedures. The digested samples were analyzed for their heavy metal content using the atomic absorption spectrophotometer (Nor *et al.*, 2012; Iwegbue *et al.*, 2013).

Physicochemical Properties of Soil

Soil pH was measured with a pH meter at a 2.5:1 ratio of deionised water to soil sample mixture. (Uwumarongie *et al.*, 2008). Electrical conductivity of the soil (ratio 1:5 of soil to water suspension) was measured with an EC meter calibrated to a 1412 μScm^{-1} calibration standard at 25°C. The gravimetric method of moisture estimation was employed to estimate soil moisture (loss-on- ignition). 1.0g of soil sample was weighed into a pre-weighed crucible and oven dried at 110°C for 6 hours until constant weight was obtained (Mostsara and Roy, 2008).

Data Analysis

IBM SPSS Statistics package was used to determine the descriptive statistics of the physico-chemical properties and trace metal concentrations; estimate the correlations and derive the linear equations in this work. The statistical variations were considered significant at $p < 0.05$. The validity of the models was confirmed through statistical tests such as the critical coefficient of the data pairs and residual statistics.

Results and Discussion

Physico-Chemical Parameters and concentration of Pb and Mn for Modelling in the Soil Samples

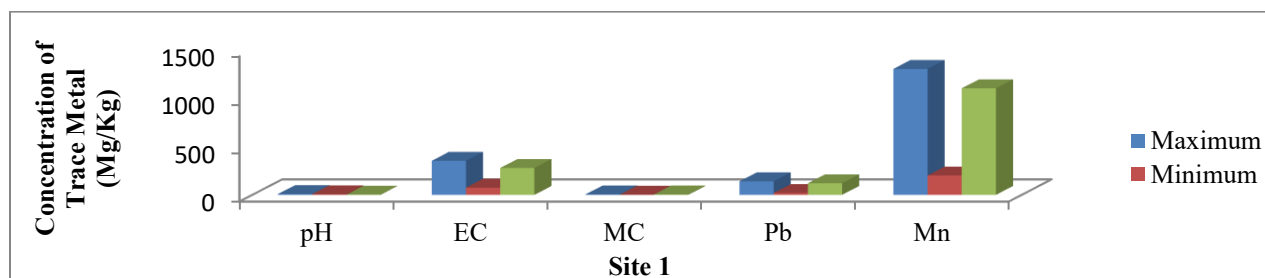


Figure 1 Physico-Chemical Parameters and Trace Metals Contents of the sampled locations in Yelwa Tudun

The descriptive statistics of the physico-chemical properties and heavy metal concentrations of soil samples collected to build the models in the study sites are presented in Figures 1 - 3.

In Figure 1, the range of values obtained for the parameters studied in Site 1 were between

8.28 - 7.11 for pH, 197.55 - 352.00 μScm^{-1} for EC and 3.16 - 5.33 for % MC. Mn concentration had the maximum concentration (1300mg/kg) was in this site. Minimum and maximum values obtained for the parameters studied in Site 2 (Figure 2) were pH (6.46, 7.22), EC (μScm^{-1}) (24.70, 81.79), Pb (30.00, 130.00 mg/kg) and Mn (100.00, 600.00 mg/kg).

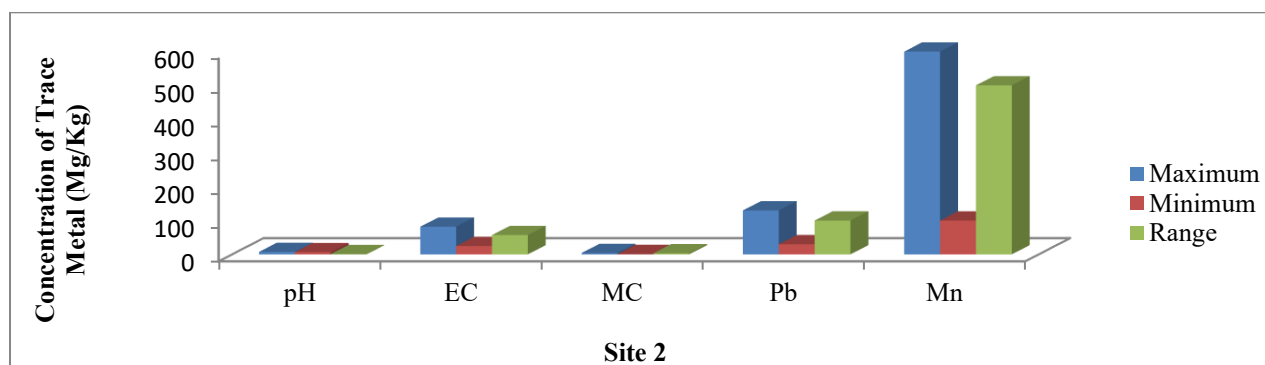


Figure 2 Physico-Chemical Parameters and Trace Metals Contents (mg/kg) of the sampled locations in Jos Road

In site 3, the minimum and maximum values of the physico - chemical parameters studied are pH (6.86, 7.79), EC (μScm^{-1}) (179.20, 345.00), %MC (1.09, 4.24), Pb (24.00, 135.00 mg/kg) and Mn (500.00, 1300.00 mg/kg) (Figure 3).

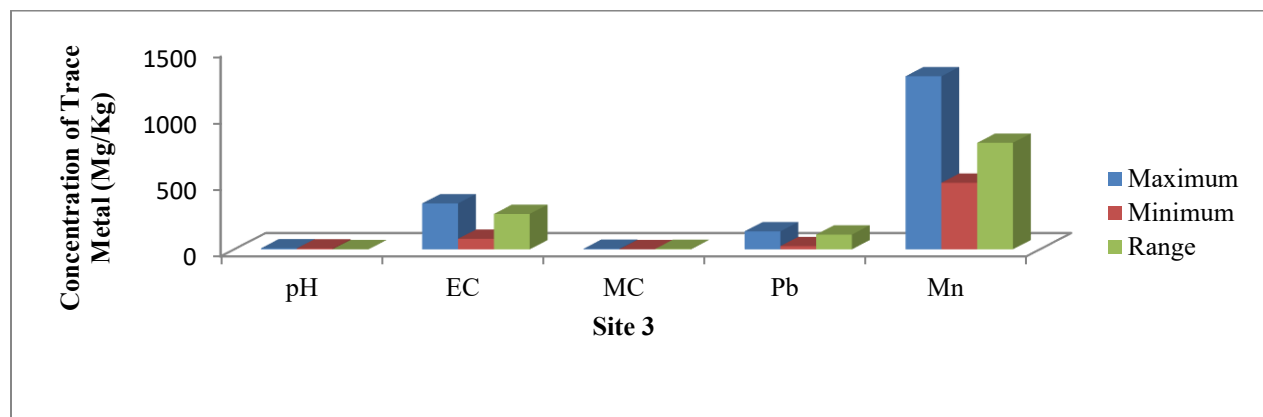


Figure 3 Physico-Chemical Parameters and Trace Metals Contents (mg/kg) of the sampled locations in Site3

Table 1 The model summary of the study metals in the various study sites

Metals	R	R Square	Adjusted R Square	Linear Regression	Model Type
Site 1					
Pb	0.889	0.790	0.764	Pb = - 9.914 + .448EC	Linear
	0.869	0.756	0.725	Pb = 81.919 ln(EC) - 345.667	Logarithmic
Mn	0.914	0.836	0.815	Mn = - 203.06 + 0.47EC	Linear
	0.880	0.775	0.747	Mn = 805.59 ln(EC) - 3491.26	Logarithmic
Site 2					
Pb	0.909	0.827	0.805	Pb = 3.619 + 25.46MC	Linear
	0.857	0.734	0.701	Pb = 50.83 ln(MC) + 25.136	Logarithmic
Mn	0.901	0.812	0.758	Mn = - 2165.36 + 303.70pH + 4.22EC	Linear
Site 3					
Pb	0.829	0.687	0.648	Pb = 29.53 + 0.305EC	Linear
	0.866	0.751	0.719	Pb = 63.902 ln(EC) - 240.112	Logarithmic
Mn	0.915	0.838	0.757	Mn = 454.5 + 2.385 EC	Linear
	0.697	0.485	0.421	Mn = 497.5 ln(EC) - 1642.234	Logarithmic

Results and Discussion

The model summary for the investigated metals (Pb and Mn) across the three contaminated sites is presented in **Table 1**. Both **linear** and **logarithmic regression models** were evaluated to determine the best fit for predicting metal concentrations using measured soil physico-chemical parameters. The correlation coefficients (**R**) between the observed and predicted values of the dependent variable (metal concentration) were consistently high, ranging from **0.688** to **0.951**, indicating strong associations between predicted and actual concentrations. This suggests that the developed regression equations provided a good fit to the observed data and can reliably predict metal concentrations from the chosen predictor variables.

The **coefficient of determination (R^2)** and **adjusted R^2 values**—which describe the proportion of variance in the dependent variable explained by the model—were generally high (**> 0.700**) for most sites, except for the linear regression model of Pb in Site 3. The high adjusted R^2 values imply that the models developed are statistically robust and capable of predicting Mn and Pb concentrations with acceptable precision. Although both linear and logarithmic relationships produced good fits, the **linear models** generally demonstrated stronger predictive power, except for Mn in Site 3, where the logarithmic form performed slightly better.

The results of this study are consistent with findings reported by previous researchers who successfully applied regression modeling to predict trace-metal behavior in soils. For instance, Paul-Olivier et al. (2013) used multiple linear regression models incorporating predictors such as Al, Fe, Mg, Mn, and Na to estimate trace-metal concentrations in calcareous and non-calcareous soils, achieving adjusted R^2 values between **0.320** and **0.990**. Similarly, Lawan et al. (2012) developed linear regression curves to model the mobility factors of Cu, Mn, and Pb in dumpsites, using background soil concentrations as predictor variables.

In the present study, **electrical conductivity (EC)** emerged as the dominant predictor variable for both Pb and Mn concentrations in most sites, except in Site 2 where **pH**, in addition to EC, significantly influenced Mn prediction. The strong relationship between EC and heavy-metal concentrations suggests that variations in soil EC reflect the accumulation and mobility of ionic substances derived from metal-rich wastes. This observation corroborates the reports of Okeke et al. (2018), who found that Cd concentrations in contaminated soils were strongly correlated with EC, with both linear and logarithmic models explaining approximately **98%** of the variation in Cd levels. Likewise, Okeke and Murtala (2022) reported that EC accounted for about **80%** of the variation in Cr concentration in contaminated soils, confirming EC as a reliable indicator of metal enrichment.

The strong association between EC and trace-metal concentrations can be attributed to the increased ionic strength and soluble salt content of soils near waste dumpsites. As metallic components of discarded materials corrode and degrade, they release ions into the soil, increasing overall conductivity. Furthermore, the interaction between spilled acids from discarded batteries and metallic scraps leads to the formation of soluble, ionizable inorganic salts that elevate EC (Alloway, 1996; Tucker et al., 2003; Okoro et al., 2013; Osakwe, 2014). Consequently, **measuring soil EC** provides an indirect yet effective means of assessing soil contamination and chemical composition (Seifi et al., 2010).

In particular, the **multiple linear regression model** developed for Mn in Site 2, using both pH and EC as predictors, achieved an **adjusted R² of 0.758**, indicating that approximately **75.8%** of the variability in Mn concentration was explained by these two soil parameters. This strong explanatory power demonstrates the combined influence of soil acidity and electrical conductivity on Mn availability and mobility. These findings are consistent with those of Atulegwu et al. (2013) and Pardo (2000), who emphasized the critical role of pH in controlling heavy-metal solubility, adsorption, and distribution in contaminated soils. The results also align with the conclusions of Haiyan et al. (2013), who observed that soil acidity significantly influences the accumulation and retention of metals such as Pb, Zn, and Mn in polluted environments.

Overall, the regression models developed in this study demonstrate high predictive efficiency and compare favorably with established models in the literature. Their application offers a rapid, cost-effective, and scientifically sound approach for monitoring heavy-metal contamination in urban soils, particularly where laboratory-based analyses are limited by cost and logistics.

Conclusion

The findings of this study confirm that **lead (Pb)** and **manganese (Mn)** concentrations in the investigated soils exhibit strong positive relationships with **electrical conductivity (EC)**, while **pH** also plays a significant role in certain sites. EC was identified as the most consistent and dominant predictor variable, capable of estimating both Pb and Mn concentrations across most locations. In Site 2, the inclusion of pH improved Mn prediction accuracy, underscoring the importance of soil chemical balance in metal retention and mobility.

The regression equations developed from this study provide a reliable mathematical framework for predicting Pb and Mn concentrations in the soils of Bauchi Local Government Area. By substituting measured soil EC, pH, or moisture content values into the model equations, metal concentrations can be estimated with high accuracy. These models offer a practical alternative to routine laboratory analyses, enabling **continuous, low-cost environmental monitoring** of contaminated sites.

In conclusion, the regression models developed are suitable for **environmental surveillance, pollution assessment, and decision-making**

related to soil quality management in the study area. Their integration into environmental monitoring programs will facilitate early detection of contamination, support remediation planning, and enhance sustainable urban land-use management. Future research should consider incorporating additional parameters such as soil organic matter, cation exchange capacity, and particle-size distribution to further improve model precision and predictive performance.

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