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Prediction Model Based on Transfer Characteristics of Heavy Metals from Soils to Yam Tubers Grown in Wukari Farmland

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Abstract

Heavy metal contamination in agricultural soils poses a significant threat to human health because these elements accumulate in food crops. The study's aim was to make a prediction model based on the soil's properties that would show how well yam tubers would take up six heavy metals (Pb, Cd, Cr, Cu, Ni, and Zn) in Wukari farmland soils. Soil and plant samples were collected from different locations within Wukari, and the physiochemical properties of the soils, along with the concentration of heavy metals, were determined. For the yam tubers, the samples were peeled, washed, dried, pulverized, and then analyzed for heavy metals with the atomic absorption spectrophotometer (AAS). Step-wise linear regression analysis was employed to develop a prediction model to estimate the potential uptake of heavy metals by yam tubers based on the soil properties. The results showed that the farmland sample soils are sandy loamy and slightly alkaline, with a mean pH of about 7.88. The prediction model demonstrated good performance in predicting the uptake of all six heavy metals, with R^2 ranging from 0.683 (Pb) to 0.998 (Zn) in the fitted empirical model. This work's findings will provide other researchers with a cost-effective tool for assessing potential contamination based on readily available soil data.

Keywords: Heavy metals, Transfer factor, Prediction model, Yam tubers, Farmland soils, Soil properties

INTRODUCTION

Tubers play a crucial role in the dietary patterns of early human evolution and have been identified as the primary staple crops with a long history of cultivation in tropical and sub-tropical regions [1]. Heavy metals are natural constituents of several ecosystems and the process of heavy metal uptake and accumulation in plants occurs through either the roots or the surfaces of leaves, as described by Sawidis *et al.*, [2]. Several factors have been identified that can influence the uptake of metals, including soil pH, metal solubility, conductivity, plant growth 'phases, plant species, soil type, and the application of fertilizers [3-4].

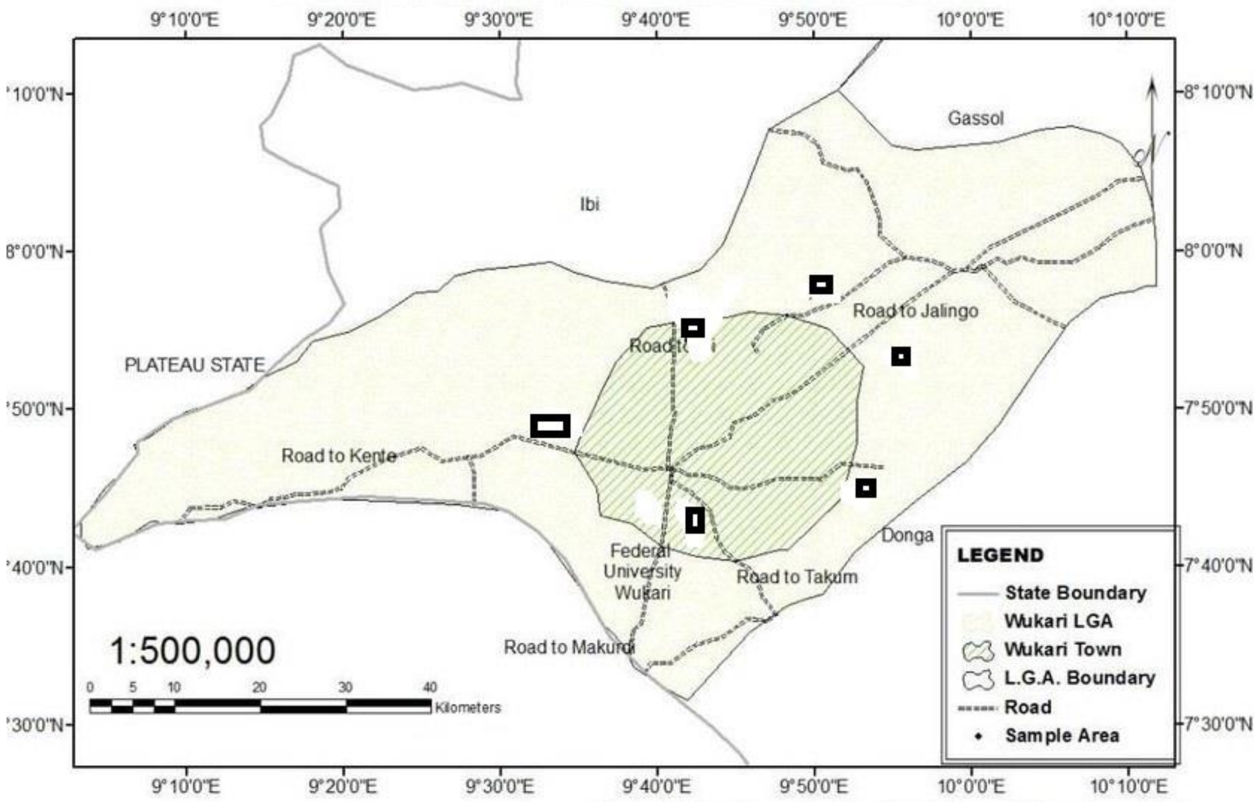
Soil to plant transfer is one of the major pathways by which heavy metals and other contaminants in soils enter the food chain [5]. According to Sarwar *et al.,* [6], individual plants have different capacities to absorb and accumulate heavy metals which lead to contamination of the food chain. This situation causes varying degrees of illness based on acute and chronic exposures [7]. Due to their non-degradable and persistent nature, heavy metals which enter the body through food, air, and water are accumulated in vital organs in the human body such as the kidneys, bones, and liver and are associated with numerous serious health disorders [8]. Research has also shown that the accumulation of heavy metals in the human body can also cause, gastrointestinal and kidney dysfunction, nervous systems disorder, skin lesion, vascular damage, immune system dysfunction, birth defects, and cancers among others. [9].

Eid *et al.,* [10] in their review suggested measuring how much metal plants take in and move around internally (bio concentration and translocation). However, this method has drawbacks. It doesn't consider the specific conditions of a particular field and may not accurately predict how different soil types affect how much metal gets into plants. Nevertheless, there is a better way to predict how much heavy metal ends up in tubers. It involves using computer models (regression models) that take into account various soil properties like acidity (pH), organic matter content, and the amount of heavy metals already present in the soil [11]. The benefit of these models is that they can predict how much metal plants will take up based on the specific soil conditions [11-13]. Even better, they can help identify which soil characteristics make a big difference in metal uptake, and potentially what can be done to reduce that uptake [14]. This could ultimately lower the amount of heavy metal entering our food chain and protect the health of living things. Hence **this research focuses on developing new mathematical models to predict the levels of six heavy metals in yam tubers.** These models will consider various soil properties as factors influencing the amount of heavy metal uptake. These factors include the existing amount of heavy metals in the soil itself, the acidity (pH) of the soil, the amount of organic materials present, cation exchange capacity, and soil water holding capacity, porosity of the soil and the temperature of the soil.

MATERIALS AND METHODS

Study Area

The research was conducted in the Wukari local government area of Taraba state. The geographical coordinates of the location are 9°47`E longitude and 7°51`N latitude, in the southern region of Taraba State, Nigeria. Wukari is known for its extensive yam cultivation.



SOURCE: GIS and Remote Sensing Lab, Kwararafa University, Wukari

Figure 1: Map of the Study Area **[**15]

Sample Collection

Six sampling locations, namely STA (mechanic village), STB (Tsokundi road area), STC (Jalingo road area), STD (Ibi road area), STE (Kente road area), and STF (Rafin kada road area), were selected in a randomized manner, taking into consideration the level of human-induced activities in the area, such as garbage disposal and mechanic workshops. The collection of soil and plant samples occurs concurrently during the optimal harvest period in October. Yam tubers were obtained from agricultural fields located in the vicinity of the designated sites. Additionally, soil samples were gathered from these farms. Soil samples were obtained from the rhizosphere of each plant, namely at a depth of around 15-20 cm.

Samples Preparation

The soil samples underwent a process of air drying, crushing, and sieving using a 2 mm screen. To analyze heavy metals, a precise amount of 5 grams was measured for each sample and placed in a silica dish that had been thoroughly cleaned and dried. The dish was then covered and subjected to a temperature of 500 °C in a furnace for duration of 6 hours. This process continued until a residue of grey-white ash was obtained. The lid of the dish was lifted to facilitate the release of gases. In order to facilitate dissolution, a 10% hydrochloric acid (HCl) solution was added to cold ash samples, followed by the addition of a 10% nitric acid (HNO_3) solution. The mixture was then placed on a water bath to ensure complete dissolution. The solution was transferred into a clean and dry volumetric flask of standard size. Distilled water was used to get the filtrate to a final volume of 100 ml. The samples were appropriately labeled and prepared for analysis using atomic absorption spectrometry (AAS).

The yam tubers samples were peeled and washed three times with distilled water and allowed to dry at room temperature for one week and then oven dried to constant weight at 65 ^{o}C using drying oven. The dried samples were homogenized (ground to powder) using laboratory ceramic mortar and pestle. The homogenized samples were sieved with 2 mm sieve to obtain fine particle size for easy digestion.

The physiochemical analysis of the soil

Determination of pH. The pH of the soil sample were determined using a Jewniary digital pH

meter in a sample to water ratio of 1:10 that is twenty grams (20g) of each sample was weighed in a beaker. Then two hundred milliliters (200ml) of distilled water was added to it. The pH electrode was dipped into the solution and the reading was accurately recorded.

Determination of Total Organic Carbon (TOC). One (1) grams of the sample can be weighed then 10mls of 0.5M $K_2Cr_2O_7$ added to it followed by 20ml of concentrated H_2SO_4. The organic carbon was determined by the Walkey black method.

Determination of the Heavy Metal Concentration. The concentrated samples were subjected to heavy metal analysis using the UNICAM 929 Atomic Absorption Spectrophotometer (AAS). The specimen was introduced into an acetylene flame that was ignited using a hollow cathode lamp emitting light at a specified wavelength characteristic of the metal lamp employed for the analysis. The metals under investigation were subjected to analysis using the ASTM method, which refers to the Standard Test Methods.

Prediction Model for transfer factor

Transfer Factor (TF)

The results for soil and the tuber crops were employed to determine the transfer factor (TF) as given in the following equation.

$$TF = \frac{[\text{Heavy metals }]\text{tubercrops mg}.kg^{-1}}{[\text{Heavy metals }]\text{soil mg}.kg^{-1}} \qquad [1]$$

Where [Heavy metals] tuber crops mg kg^{-1} Concentration of heavy metal in tuber crops (mg/kg); [Heavy metal] soil mg kg^{-1} Concentration of heavy metal in the soil (mg/kg).

Prediction Model

Prediction models for the transfer of heavy metals between the soil and the tuber crops were established through stepwise linear regression. These models are based on the equation below:

$$\text{TF} = a\times\text{pH}+b\times\text{OM}+c\times\text{CEC}+d\times\text{OC}+e\times\text{Temp}+f\times\text{soil texture}+g\times\text{heavy metals in soil}+k \qquad [2].$$

where, TF, OM, CEC, OC, TEMP, soil texture and heavy metals soils are values of the concentration of organic matter (g/kg) in soils, the cation exchange capacity (cmol/kg) of soils, the concentration of organic carbon (g/kg) in soils, the soil temperature, soil clay, silt and sand content (g/kg) in soils, and the concentration of heavy metal in soil (mg/kg) respectively. The soil property parameters a, b, c, d, e, f, and g indicate the impacts of the soil properties on Heavy metal accumulation in tuber crops, respectively. The intercept k is the intrinsic sensitivity that characterizes the ability of tuber to absorb the particular heavy metal.

RESULTS AND DISCUSSION

Table 1: Physiochemical Properties of the Soil

Properties	Range	Mean
pH	6.50 – 8.77	7.88 ± 0.78
Temp (°C)	27.00 – 29.00	28.17 ± 0.75
SWC (%)	21.04 – 26.13	22.85 ± 2.23
CEC (%)	8.78 – 9.42	9.25 ± 0.26
O.C (%)	0.50 – 1.05	0.73 ± 0.21
O.M (%)	0.86 – 1.81	1.26 ± 0.37
Silt (%)	14.80 – 28.80	19.80 ± 4.86
Clay (%)	2.00 – 8.00	5.00 ± 2.10
Sand (%)	63.20 – 83.20	75.20 ± 6.22

SWC (Soil water holding capacity); CEC (Cation exchange capacity); O.C (Organic carbon); O.M (Organic matter).

The results in Table 1 shows the mean value at different ranges of the physiochemical properties of the soil sample from six (6) locations (where n=3).

Table 2: Transfer factor of heavy metals from soil to tubers

SAMPLES	PARAMETERS					
	TRANSFER FACTOR					
YAM	Pb	Cd	Cr	Cu	Zn	Ni
A	0.249502	0.526320	1.000000	0.500000	0.571429	0.352734
B	0.656393	0.100000	0.666667	ND	0.353045	0.187617
C	0.426979	0.240000	0.500000	1.000000	0.244948	0.176367
D	0.297597	0.100000	0.333333	ND	0.214286	0.544959
E	0.329854	0.258060	0.333333	ND	0.142857	0.333333
F	0.182841	1.055560	0.500000	3.030303	0.4000000	ND

A to F represent test samples

ND = Not detected

The average transfer factor from soil to yam tubers for all the elements range from Pb (0.18 -0.66), Cd (0.1-1.1), Cr (0.3 - 1.0), Cu (ND - 3.0), Zn (0.14 – 0.57), and Ni (ND – 0.5), the sequence of the transfer factor for yam tuber is Cu > Cd >Cr > Pb >Zn > Ni

Table 3: Transfer Factor Prediction Model for the plants

Samples/metals	Prediction model	R^2	RMSE
Yam			
Pb	TF= 6.137+0.26784PH – 0.26474temp – 0.16082OM – 0.0221246Pb_{soil}	0.643	0.2270
Cd	Tf =- 14.801 -0.38267PH + 0.63721temp – 0.21243OM + 0.23375Cd_{soil}	0.982	0.0201
Cr	Tf= 0.93219 +0.28614pH – 0.086592temp - 0.56113OM +1.9334Cr_{soil}	0.962	0.0289
Cu	Tf = 1.3167 – 0.27702pH + 0.20631temp – 2.0523OM – 0.12961Cu_{soil}	0.948	0.0603
Zn	Tf =6.0033 +0.20943pH – 0.23351temp – 0.27618OM – 0.0036091Zn_{soil}	0.998	0.0640
Ni	TF= 15. 578 +0.4954pH – 0.60633Temp -0.8879OM - 0.022603Ni_{soil}	0.927	0.1113

TF = Transfer factor; R^2 =coefficient of determination, RMSE = Root mean square error

The prediction model for the plants revealed R^2 values of Yam in this order (Zn>Cd>Cr>Cu>Ni>Pb) that is, it range from (0.643- 0.927);

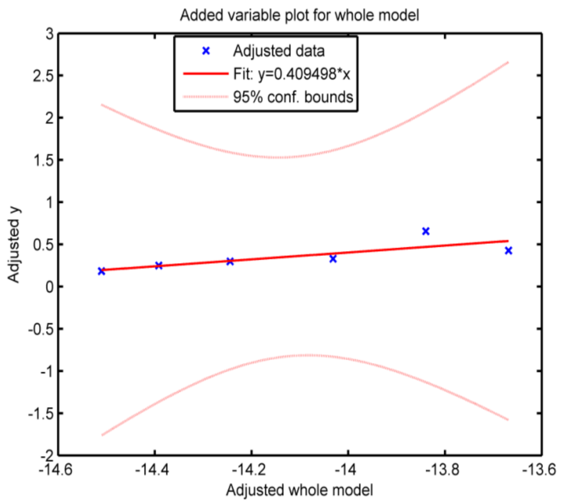


Figure 1: Model of Lead Transfer Factor in yam

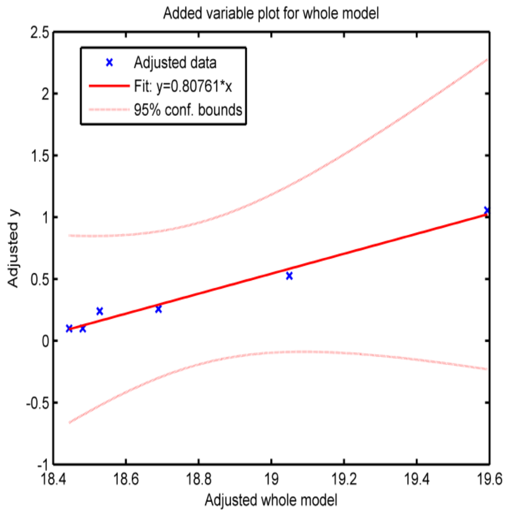


Figure 2: Model of Cadmium Transfer Factor in yam

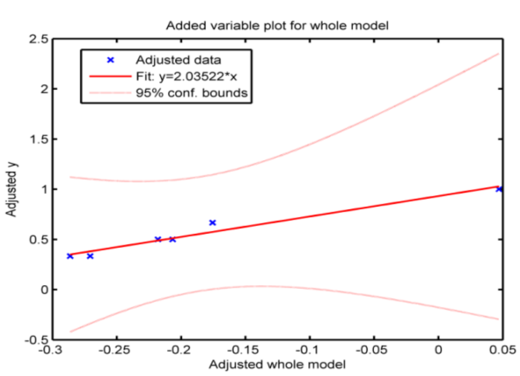


Figure 3: Model of Chromium Transfer Factor in yam

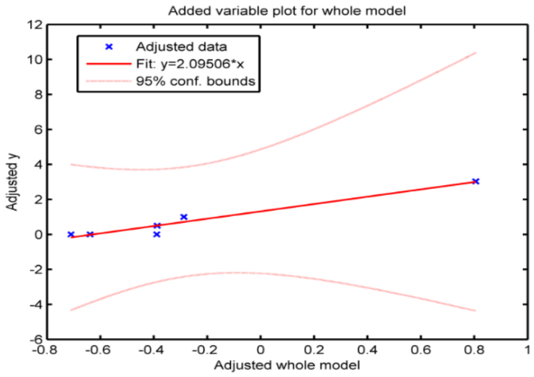


Figure 4.: Model of Copper Transfer Factor in yam

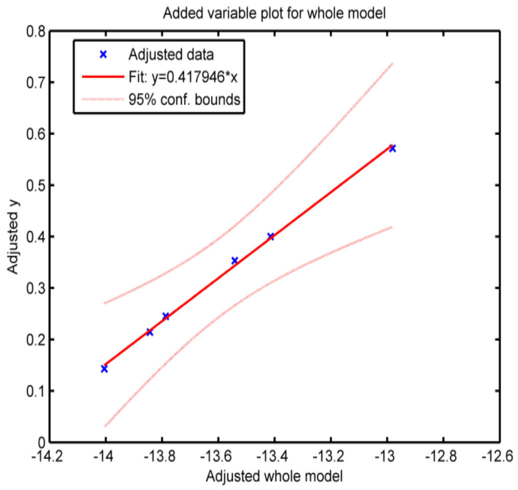


Figure 5: Model of Zinc Transfer Factor in yam

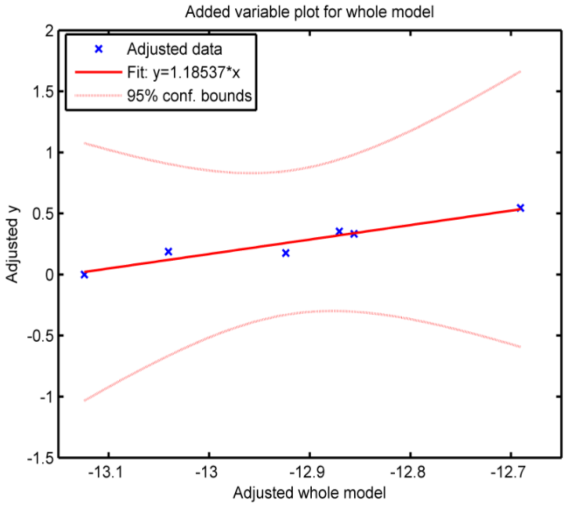


Figure 6: Model of Nickel Transfer Factor in yam

DISCUSSION

Based on the ratios of heavy metal concentration in tuber crops and soil, the transfer factors from soil to crops were calculated and are shown in Table 1. The average transfer factor from soil to yam tubers for all the elements ranged from Pb (0.18 -0.66), Cd (0.1-1.1), Cr (0.3 - 1.0), Cu (ND - 3.0), Zn (0.14 – 0.57), and Ni (ND – 0.5), the sequence of the transfer factor for yam tuber is Cu > Cd >Cr > Pb >Zn > Ni, indicating that the transfer of the heavy metal is moderate except for Cu at site F with transfer factor of 3.03. The transfer factor of Cr at Site A is 1 implying equilibrium state between the soil and the plant. When the transfer factor is greater than 1, it implies that plant has a high uptake efficiency for that metal and for the transfer factor that is below one means there is a possibility that soil serves as the primary source of metal bioaccumulation in plants. Nevertheless, the study conducted by Mwegoha and Kihampa [16], shown that there is not always a direct correlation between total metal concentrations in soil and the bioavailability of metals in plants, particularly when the value exceeds one. The bioavailability of heavy metals is influenced by various physicochemical parameters, including pH, organic matter (OM) concentration, cation exchange capacity, redox potential, soil texture, and clay content. The correlation of transfer factor for Pb with the soil physiochemical properties resulted to a positive regression with coefficient of 0.2678, for pH, and negative regression for the temperature, OM and the metal concentration in the soil as shown in Table 3. This shows that the pH with high coefficient is the soil parameters having high influence on the transfer of Pb from soil to yam tuber. Similarly Cr, Zn, Ni also follows same trend with the pH having the highest coefficient signifying that the soil pH is the main factor affecting the accumulation of the heavy metals in yam tubers. Cd and Cu have a negative correlation with the soil pH and a positive correlation with the soil Temperature. Site F have the highest value of transfer factor for Cd (1.1) and Cu (3.0) implying that the plant is actively taking up and accumulating heavy metals from the soil at a higher rate than they are being released. This could indicate that the plant is accumulating high levels of heavy metals which may have potential implication for food safety and environmental health

The predictive models established by linear regression on MATLAB are shown in Fig 1 – 6 and Table 3. The chemical behavior of heavy metals is complex, and many factors such as soil pH, OM concentration, CEC, Temperature, soil texture etc. affect their uptake by plants as reported by Chapman *et al.*, [17]. According to Liu *et al.,* [18] empirical regression can be used to estimate the rate of accumulation or transfer of heavy metals from soil to crops.

In the present study, predictive models were developed for the transfer factor of heavy metals from soil to the tubers through the stepwise linear regressions model on MATLAB to examine the relationship between the metals uptake by the yam and soil pH, OM concentration, CEC, Temp, SWC, OC content, and soil texture. The predictive model developed for this work are similar for all the metals as the TF mainly depend on Soil pH, OM content, Temp and metal concentration in the soil, though Significant difference was found in the coefficients of the models. For example, the pH coefficient in the prediction model for Pb is 0.2678 as shown on Figure 1 while the parameter for Cd is only 0.3827 as seen in Figure 2. Rafiq *et al.,* [19], reported that Cd phytoavailability to Pak - choi was significantly affected by soil pH, organic matter and total Zn and Cd concentrations, and the R^2 of the stepwise regression model in their report was 0.977. Furthermore, Hu *et al.,* [20], through stepwise regression found that soil pH is the main factor affecting Hg accumulation in corn grain with R^2 value of 0.81. A RMSE ≤ 0.5 suggested that the model-predicted heavy metal content exhibited good agreement with the measured value and reflects a suitable model goodness of fit TF prediction models developed for the tubers could be used to predict Pb, Cd, Cr, Zn and Ni TF values for other non-model tubers with similar soil physiochemical properties, therefore the results from the present study provide further evidence to support the extrapolation of metal TF to other non-model tubers varieties. However, further investigation is required to improve the model performance, especially for Ni and Pb in yam. More work is needed to understand the migration mechanism of various heavy metals in the soil–tuber system and to accurately identify the main influencing factors.

CONCLUSION

Factors influencing the transfer of metals from soils to tubers were identified, and models were developed to predict how these metals accumulate in the soil-tuber system. Transfer factors from soil to plants indicated that heavy metal accumulation in crops was generally moderate across all sampled sites and crops, except for Cu and Cd in site F, where the transfer factor exceeded 1, indicating high accumulation. The robust regression models performed well, demonstrating high efficiency with minimal parameter errors. A key advantage of these models is their time and cost-effectiveness, as they reduce the data requirements needed to determine statistically significant soil characteristics. These models could be valuable for assessing the safe cultivation of yam tubers in soil concurrently evaluating potential risks to human health. The developed models address the limitations of transfer factors (BCFs) by identifying soil characteristics that significantly affect heavy metal accumulation in yam tubers. They can help pinpoint factors that need regulation to reduce heavy metal entry into the food chain, thereby mitigating risks to organisms. The variability explained by the models influences their reliability, emphasizing the importance of utilizing them with a clear understanding of their explanatory power.

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