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Prediction Models Founded on Soil Characteristics for the Estimated Uptake of Nine Metals by Okra Plant, *Abelmoschus esculentus* (L.) Moench., Cultivated in Agricultural Soils Modified with Varying Sewage Sludge Concentrations

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Abstract: Prediction models were developed to estimate the extent to which the metals Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb, and Zn were taken up by the fruits, the leaves, the stems, and the roots of the okra plant, *Abelmoschus esculentus* (L.) Moench., grown under greenhouse conditions in soil modified with a spectrum of sewage sludge concentrations: 0, 10, 20, 30, 40, and 50 g/kg. All the metals under investigation, apart from Cd, were more concentrated in the *A. esculentus* roots than in any other organ. Overall, the sum of the metal concentration (mg/kg) within the varying plant tissues can be ranked in the following order: roots (13,795.5) > leaves (1252.7) > fruits (489.3) > stems (469.6). For five of the metals (i.e., Cd, Co, Fe, Mn, and Pb), the BCF was <1; for the remaining four metals, the BCF was >1, (i.e., Cr, 1.074; Cu, 1.347; Ni, 1.576; and Zn, 1.031). The metal BCFs were negatively correlated with the pH of the soil and positively correlated with soil OM content. The above-ground tissues exhibited a TF < 1 for all metals, apart from Cd with respect to the leaves (2.003) and the fruits (2.489), and with the exception of Mn in relation to the leaves (1.149). Further positive associations were demonstrated for the concentrations of all the metals in each examined plant tissue and the corresponding soil metal concentration. The tissue uptakes of the nine metals were negatively correlated with soil pH, but positively associated with the OM content in the soil. The generated models showed high performance accuracy; students' *t*-tests indicated that any differences between the measured and forecasted concentrations of the nine metals within the four tissue types of *A. esculentus* failed to reach significance. It can, therefore, be surmised that the prediction models described in the current research form a feasible method with which to determine the safety and risk to human health when cultivating the tested species in soils modified with sewage sludge.

Keywords: bioconcentration factor; biosolids; metals; okra; regression models; translocation factor

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1. Introduction

The technical implications involved in the proper disposal of modern municipal wastes have made it essential to develop alternative waste management approaches that reduce the environmental impacts resulting from improper disposal [1]. Metropolitan waste materials such as bio-solids (e.g., sewage sludge) contain high concentrations of key nutrients for crops including trace elements as well as micro and macro-nutrients. These

have the potential to enrich growing media and thus reduce the requirement for chemical fertilisation. Nevertheless, a notable disadvantage in the use of bio-solids is the risk that they may contain toxic metals, which restrict their agricultural applications [1].

Metals are a particular group of elements that, unlike organic pollutants, cannot be degraded through biological processes [2]. Increased attention has been focused on metals due to their harmful negative effects on the environment [3]. Usually, the most important avenues of exposure are the consumption of contaminated foods, the inhalation of suspended air particles, the direct ingestion of soil, and the consumption of contaminated drinking water [4,5]. Metal contamination may originate from both natural geochemical processes (e.g., weathering of ultramafic rocks) and anthropogenic sources [6]. Direct anthropogenic sources of metals affecting the environment are fertilizers, pesticides, mining, electroplating, industrial effluents, sewage sludge, and atmospheric deposition [7].

In *Abelmoschus esculentus* (L.) Moench. (i.e., the okra plant), the accumulation of Cd has had an adverse impact on its biological and biochemical properties, cultivation, and harvest [8], thus implying that *A. esculentus* is not an appropriate species to be grown in soil containing significant Cd levels. It was subsequently demonstrated that a combination of Cd and Zn enhanced Zn accretion but diminished Cd uptake in the plant's roots, stems, and leaves. It was concluded that the two metals demonstrated antagonistic actions when utilised together, leading to a lower absorption of Cd. Srivastava et al. [9] proposed that MSWVC has potential as an organic additive to soil, as evidenced by a high harvest rate and the antioxidative reaction of *A. esculentus* at varying MSWVC proportions of up to 60% concentration. If MSWVC were employed in the agricultural sector, it could mediate the negative impact of the increase in organic solid waste. One study reported that *A. esculentus* plants were found to have the following metal concentrations (mg/kg): Mo, 7.0–9.3; Fe, 39.7–44.1; Cu, 11.8–19.8; Zn, 28.2–37.1; Ni, 6.1–9.3; Pb, 4.9–7.1; Cd, 3.4–4.2; and Co, 0.1–0.3 [10]. These concentrations were under the maximum of permitted metal levels in plant specimens, with the exceptions of Mo and Cd. Using wastewater for irrigation heightened the fertile properties of the soil, and only a fraction of the metals contained in the wastewater accumulated in the plants' tissues [11]. A further study noted that the deployment of 100% distillery effluent for irrigation elevated Zn, Cu, Cd, Ni, and Cr levels, but diminished the number of soil microorganisms, i.e., bacteria, fungi, and actinomycetes [12]. In the soil and in *A. esculentus*, the metal concentrations were ranked Ni > Cr > Cd > Zn > Cu and Ni > Cr > Cu > Cd > Zn, respectively. The metal concentrations (in mg/kg) were all under the recommended permissible limit (for plants, Cd: 0.2–1.5, Ni: 1.5–10, Cu: 40, and Zn: 50–100; for soil: Cd: 0.06–6, Ni: 30–150, Cr: 100, and Zn: 50–600) [12].

To reduce the toxic effects of metal and their translocation to food chains, it is important to estimate the impact of soil variables on the bioavailability and uptake of metals by plants [13]. The simple estimation of the BCF can serve as a rough insight into the range of metal uptake, but it does not reflect more detailed site-specific conditions of the soil [14]. Valuable mathematical approaches and regression models can be applied to forecast specific dependent variables (e.g., metal concentrations within plant tissues) using variables independent of the soil (e.g., metal concentration, pH, and OM content) [13,15–17]. Once generated, such models can be employed to determine the impact of sewage sludge use with respect to crops such as *A. esculentus*. To date, no regression models for the absorption of metals by *A. esculentus* grown in soil modified with sewage sludge have been established. Thus, the present study aims to establish mathematical regression models that include specific soil parameters as explanatory independent variables (i.e., metals, pH, and OM content) to predict the concentration of the most common metals (Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb, and Zn [18]) in the four tissues of *A. esculentus* (i.e., fruit, leaf, stem, and root) cultivated in soils amended with different proportions of sewage sludge. It is predicted that these models may improve the assessment of the hazards associated with the use of sewage sludge for crops and assist investigations into the safety of growing *A. esculentus* in soil fortified with this waste product.

2. Materials and Methods

2.1. Study Species

A. esculentus (a member of the *Malvaceae* family) originated in the paleotropical regions, but has become native to numerous temperate geographical locations. Colloquial labels for this plant include bamia, okra, gumbo, and "lady's finger". An annual vegetable and herb, this species grows up to 2 metres in height, and the plant can be smooth, hairy, or prickly, with thick stems. The leaves are approximately 20 cm in size, variably subdivided into 5–7 lobes, which again can be smooth, covered in rigid hairs overlying the veins, or with tooth-like projections, as well as with petioles of up to 10 cm in dimension. There are single flowers in the upper axils on thick pedicles of between 1 and 3 cm in length. There are 8–12 epicalyx portions of approximately 2.5 cm in size, which are linear, hairy, and of an early deciduous nature. The calyx and corolla measure 1.5–2.5 cm and 4–8 cm, respectively, and are coloured from white to vivid yellow, as well as purple or crimson at the inferior portion. The capsule has a dimension of 5–20 cm and is bristly and fleshy until baked for consumption, at which point it becomes smooth and fibrous. The seeds are 3–6 mm in size, subglobose, and vary from smooth to downy or hairy [19].

In lowland tropical regions, *A. esculentus* is grown for its unripe fruits; following the initial yield, it is often cut back to promote at least one additional harvest. It can withstand a wide spectrum of soil conditions, and a pH of between 5.5 and 8.0. However, it prefers an open, well-draining loam to which manure is added in winter, and a pH of between 6.0 and 6.7. High-quality *A. esculentus* pods may be effectively produced when planted in soils with high fertility, such as those treated with sewage sludge [20]. MSWVC showed a positive effect on biochemical, physiological, and yield responses of *A. esculentus* when grown in amended soils with up to 60% MSWVC. It is prone to attack by red spider mites and glasshouse whiteflies when grown under greenhouse conditions. In North America, corn earworm and green stinking cabbage worm are troublesome pests for its cultivation. In addition, *A. esculentus* is vulnerable to a number of fungal pathogens such as leaf spot (*Cercospora abelmoschi*), leaf and pod spot (*Ascochyta abelmoschi*), powdery mildew (*Leveillula taurica*), and verticillium wilt (*Verticillium albo-atrum*) [19].

2.2. Experimental Design

A. esculentus seeds (Clemson Spineless, West Hills Seeds, Sutter, CA, USA) were procured from the district market in Abha City. The experimental growing medium was cultivated field soil (coarse sandy loam; Typic Torriorthents [21]) acquired from between 0 and 20 cm below the ground surface from de novo reclaimed adjacent sites (latitude, 18.2434; longitude, 42.5661). Abha City Municipal Wastewater Treatment Plant (latitude, 18.2331; longitude, 42.5212) was the source of the sewage sludge. The field soil and sewage sludge underwent air-drying for 14 days prior to being pulverised and passed through a 2 mm sieve. Cultivation was conducted in a greenhouse sited at the Biology Department, King Khalid University. The sewage sludge was combined with aliquots of field soil at concentrations of 0 (control), 10, 20, 30, 40, and 50 g/kg. These were comparable to 0, 30, 60, 90, 120, and 150 t/ha, respectively, and founded in the pilot data. A total of 4 kg of the chosen intervention was placed in 6 plastic pots, each 6 litres in volume, together with 10 *A. esculentus* seeds. The pots were then set out in a randomised format. Greenhouse cultivation started on 10 February 2018 and was ongoing for 62 days under a natural diurnal cycle (Figure 1). Each pot was hydrated to 40–50% with tap water irrigation. Weeds were removed by hand, as required. The plants were thinned by hand to one plant per pot after 2 weeks.

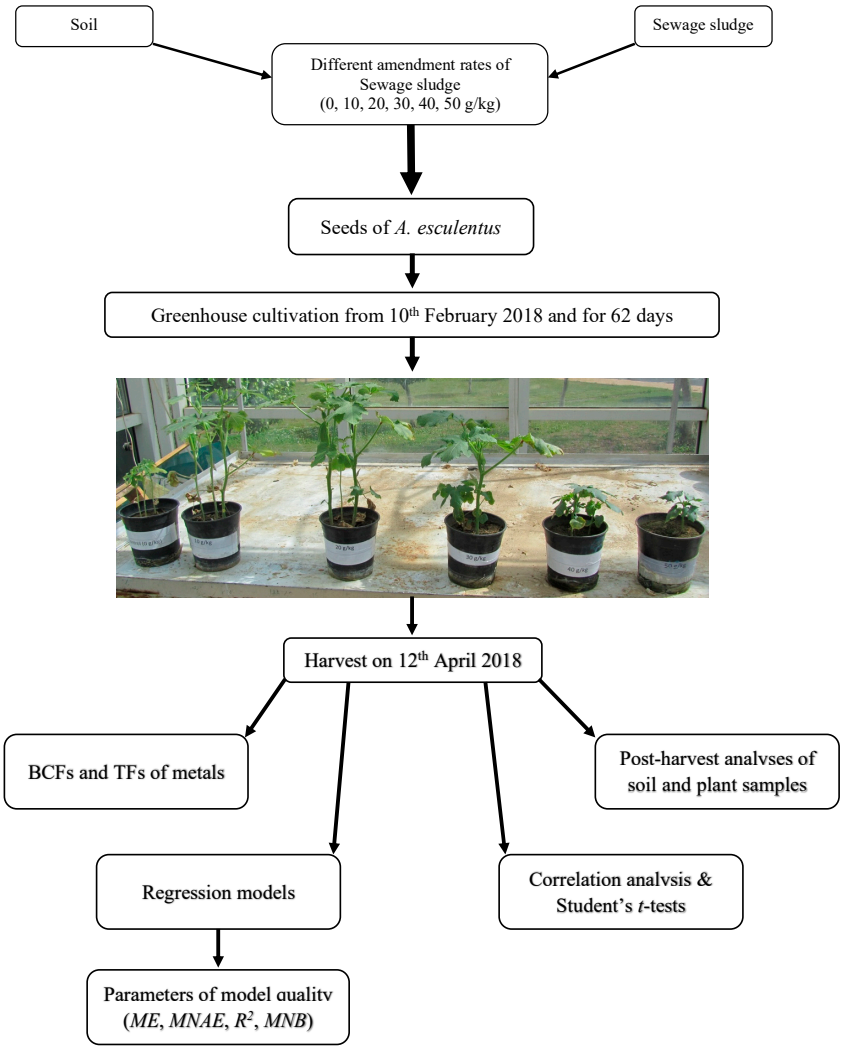


Figure 1. Flowchart represents the experimental design and sample analysis.

2.3. Sample Analysis

Harvest of all plants was performed on 12 April 2018. The plants were rinsed, first in running water and then in deionised water. The tissues were segregated into roots, stems, leaves, and fruits, and desiccated at a temperature of 60 °C for 7 days; a plastic mill (Philips HR2221/01, Philips, Shanghai, China) was then utilised for pulverising. The samples were stored until required for analysis. Soil samples from each treatment were gathered at experiment completion and then air dried for 14 days, pulverised, and then passed through a 2 mm sieve. Specimens of soil from each intervention, together with sewage sludge and field soil samples, were analysed to determine their OM contents (%); this was achieved with a loss-on-ignition technique at a temperature of 550 °C for 120 min [22]. Soil OM content is the organic matter component of soil, consisting of plant and animal detritus at various stages of decomposition, cells and tissues of soil microbes, and substances that soil microbes synthesize [22]. Soil–water (1:5) extracts were utilised to assess pH [23].

In order to gauge the concentrations of the nine metals under investigation (i.e., Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb, and Zn), a tri-acid mix (HNO_3–H_2SO_4–$HClO_4$, 5:1:1, $v/v/v$) digestion technique was applied to 0.5–1.0 g of the individual soil, sewage sludge, field soil and plant specimens with the use of a microwave sample preparation system (Perkin Elmer Titan MPS, Perkin Elmer Inc., Waltham, MA, USA). Inductively coupled plasma optical emission spectrometry (Thermo Scientific iCAP 7000 Plus Series; Thermo Fisher Scientific, Waltham, MA, USA) was used to establish the respective metal concentrations.

After each ten samples, blanks and quality control standards were measured to identify any impurities or drift. The lower levels of detection (μg/L) for the nine metals were Ni, 6.0; Co, Cr, and Cu, 2.0; Fe, Pb, and Zn,1.0; Mn, 0.3; and Cd, 0.1. All apparatus parameters and working properties were in accordance with the vendor's recommendations. System calibration was performed using standard solutions composed of predetermined metal concentrations [23].

2.4. Quality Assurance and Control

The precision of the chemical analysis methodology was ascertained utilising a certified reference material, i.e., SRM 1573a, tomato leaves. The same techniques used for *A. esculentus* samples were applied to this material for digestion and analysis. The metal digestions and assays were conducted thrice. The measured concentrations and those of the certified reference were contrasted to establish accuracy; the outcome was given as a percentage. The spectrum of recovery rates was 93.8–106.8%.

2.5. Data Analysis

To assess the potential of *A. esculentus* to accumulate metals in its root system and to convey those metals from the roots to the above-ground plant parts (i.e., stems, leaves, and fruits), the BCF and TF were computed following the method by Eid and Shaltout [24] as outlined below, where:

BCF = Metal concentration in the root (mg/kg)/Metal concentration in the soil (mg/kg);
TF_{stem} = Metal concentration in the stem (mg/kg)/Metal concentration in the root (mg/kg);
TF_{leaf} = Metal concentration in the leaf (mg/kg)/Metal concentration in the root (mg/kg);
TF_{fruit} = Metal concentration in the fruit (mg/kg)/Metal concentration in the root (mg/kg).

Any association between BCF and soil pH or BCF and OM content was evaluated using the Pearson simple linear correlation coefficient (r). The r value was also computed to identify any correlations between the soil variables (i.e., soil pH, metal concentrations, and OM content) and the metals in the plant tissues.

A total of 12 data sets were randomly selected for the fruits, leaves, stems, and roots for the validation. The remaining 24 data sets were utilised to generate the regression models to extrapolate the metal concentrations in the plant tissues and were deemed to be the dependent variable for the various soil elements. The independent variables included the Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb, and Zn concentrations individually, as well as pH and OM content, and formed the main elements utilised to define the metal concentrations within the plants [16,25]. The overall formula for the model was:

$$C_{plant} = a + (b \times C_{soil}) + (c \times pH) + (d \times OM)$$

where C_{plant} and C_{soil} represent the plant and soil metal concentration, respectively, OM is the OM content percentage of the soil, and a, b, c, and d are regression coefficients.

The model's quality was appraised by calculating *ME*, *MNAE*, R^2, and *MNB* [26] as indicated by the following equations [16]:

$$ME = 1 - \{\sum (C_{model} - C_{measured})^2 / \sum (C_{measured} - C_{mean})^2\}$$

$$MNAE = \{\sum (|C_{model} - C_{measured}| / C_{measured})\}/n$$

$$MNB = \sum (C_{model} - C_{measured}) / \sum C_{measured}$$

where C_{model}, $C_{measured}$, and C_{mean} indicate the metal concentration determined by the model, the concentration actually measured, and the average concentration, respectively, and n represents the observation number.

Students' t-tests were utilised to identify any disparities between the predicted and assayed metal concentrations for each tissue type. Associations between *ME* and the measurements of model quality (i.e., R^2, *MNAE*, and *MNB*) were appraised using the

Pearson simple linear correlation coefficient (r). The Statistical Package for the Social Sciences software, version 15.0 [27], was utilised for all data analysis.

3. Results

The highest pH noted in the field soil was 8.7. This soil also contained the greatest concentrations (mg/kg) of Cd, 2.9; Co, 35.5; Fe, 42.4 × 10^3; and Mn, 677.3. The EC and the OM content were higher in the sewage sludge, 14 mS/cm and 65.0%, respectively. The sewage sludge also demonstrated elevated concentrations (mg/kg) of Cr, 176.2; Cu, 162.6; Ni, 138.7; Pb, 671.1; and Zn, 667.6 (Table A1). Following the *A. esculentus* harvest, an alkaline pH of between 6.7 and 8.5 was measured in the soil–sludge admixture; the mean pH was 7.3, and the CV was 7.3%. The pH spectrum of the OM content was 1.6–7.5%; the mean was 4.3% and the CV, 49.6% (Table 1). In the soil modified with sewage sludge, the highest and lowest mean metal values (mg/kg) identified were for Fe, 30.9 × 10^3, and Cd, 2.8 (Table 1). The soil metal concentrations ranked in order of concentration were Fe > Mn > Cr > Zn > Ni > Co > Cu > Pb > Cd.

Table 1. Chemical characteristics of the soil amended with sewage sludge after harvesting *Abelmoschus esculentus* plants grown for 62 days.

Value	pH	OM (%)	Metal Concentration								
			Cd	Co	Cr	Cu	Fe	Mn	Ni	Pb	Zn
Minimum	6.7	1.6	1.7	23.3	34.8	2.1	14.2	203.5	18.2	2.9	56.1
Maximum	8.5	7.5	4.0	57.1	158.8	52.6	67.2	795.8	53.0	10.2	161.0
Mean (n = 36)	7.3	4.3	2.8	31.2	94.9	15.7	30.9	477.7	32.8	4.8	92.9
CV (%)	7.3	49.6	21.8	28.4	41.8	78.9	36.5	37.3	16.0	30.0	25.1
MALAS	NA	NA	1–5 [a]	20–50 [a]	50–200 [a]	60–150 [a]	20–40 [b]	>3000 [a]	20–60 [a]	20–300 [a]	100–300 [a]

All metal concentrations are in mg/kg except Fe, which is in g/kg. [a]: Kabata-Pendias [7], [b]: Cornell and Schwertmann [28].

When *A. esculentus* tissues were examined, the fruits contained the least quantity of metals, apart from Cd (Table 2). With the exception of Cd, the roots were found to have accumulated the greatest concentration of metals, as compared to the above-ground plant components. The results of the metal assays from the plant parts, ranked in descending order, were the fruits, Fe > Mn > Zn > Cu > Ni > Co > Cd > Cr > Pb; the leaves, Fe > Mn > Zn > Cu > Cr > Ni > Co > Cd > Pb; the stems, Fe > Mn > Zn > Cu > Cr > Co > Pb > Ni > Cd; and the roots, Fe > Mn > Zn > Cr > Ni > Cu > Co > Pb > Cd. Overall, the sum of the metal concentration (mg/kg) within the varying plant tissues can be ranked in the order: the roots (13,795.5) > the leaves (1252.7) > the fruits (489.3) > the stems (469.6).

For five of the metals (i.e., Cd, Co, Fe, Mn, and Pb), the BCF was <1; for the remaining four metals, the BCF was >1 (i.e., Cr, 1.074; Cu, 1.347; Ni, 1.576; and Zn, 1.031). The above-ground tissues exhibited a TF < 1 for all the metals, apart from Cd, with respect to the leaves (2.003) and the fruits (2.489) and with the exception of Mn (1.149) in relation to the leaves (Table 3). The soil pH and the BCF for all the metals were negatively associated; the highest and lowest correlations were demonstrated by Cd (r = −0.869) and Cu (r = −0.315), respectively. The soil OM content had a positive relationship with the metal BCFs, with the highest and lowest correlations exhibited by Co (r = 0.916) and Cu (r = 0.145), respectively (Figure 2). Mostly, the metal concentrations in all four *A. esculentus* tissues were positively associated with the corresponding metal concentrations in the soil (Figure 3). Several negative relationships were identified between the soil pH and the tissue metal concentrations, whereas an opposite pattern was seen in relation to the tissue metal concentrations and the soil OM content.

With respect to the fruits, the regression equation for Zn displayed the largest variation coefficient (R^2 = 0.922) and was linked with the most sizeable *ME* (0.915) and smallest *MNAE* (0.106) and *MNB* (0.005). Co demonstrated the equivalent parameters for the leaves (R^2 = 0.943; *ME*, 0.952; *MNAE*, 0.052; *MNB*, 0.000) (Table 4). Cu displayed these features for the stems (R^2 = 0.903; *ME*, 0.897; *MNAE*, 0.136; *MNB*, 0.007) and Cd, for the roots (R^2 = 0.896; *ME*, 0.886; *MNAE*, 0.182; *MNB*, 0.010). Students' t-tests indicated that any

differences between the measured and forecasted concentrations of the nine metals within the four tissue types of *A. esculentus* failed to reach significance. For all the metals in the four plant components, *MNAE* < 0.50, apart from Pb in the fruits (0.579); Ni (0.733), Pb (0.694) and Co (0.507) in the stems; and Fe (0.594) and Pb (0.528) in the roots. When *ME* was plotted along the X-axis against R^2, *MNAE,* and *MNB*, respectively, on the Y-axis, a positive simple linear correlation was noted for R^2 (0.977), and negative associations were observed for *MNAE* (−0.987) and *MNB* (−0.987) (Figure 4).

Table 2. Metal concentrations in fruits, leaves, stems, and roots of *Abelmoschus esculentus* plants harvested after 62 days.

Tissue	Value	Metal Concentration (mg/kg)								
		Cd	**Co**	**Cr**	**Cu**	**Fe**	**Mn**	**Ni**	**Pb**	**Zn**
Fruit	Minimum	0.3	0.6	0.1	4.5	45.6	33.7	0.1	0.1	21.9
	Maximum	2.2	1.8	1.0	17.6	505.5	421.9	4.1	0.7	106.0
	Mean (n = 36)	1.0	1.2	0.4	10.7	225.1	188.9	1.6	0.3	60.1
	CV (%)	79.5	35.5	91.8	35.8	78.3	75.9	85.0	55.8	43.6
Leaf	Minimum	0.2	0.8	1.7	2.6	337.6	127.1	0.0	0.0	20.1
	Maximum	1.2	2.3	13.0	11.0	1501.1	686.8	5.2	0.4	79.0
	Mean (n = 36)	0.7	1.5	5.7	7.1	810.2	379.0	1.7	0.1	46.7
	CV (%)	43.5	34.3	65.3	37.0	48.9	50.1	99.4	48.2	73.5
Stem	Minimum	0.1	0.2	0.5	0.8	103.1	9.7	0.0	0.0	10.1
	Maximum	0.6	4.2	3.9	13.1	669.8	211.0	1.4	3.9	98.8
	Mean (n = 36)	0.3	1.4	1.7	6.8	315.0	97.6	0.4	0.8	45.6
	CV (%)	49.8	67.1	55.6	61.1	57.9	73.0	97.4	128.4	62.5
Root	Minimum	0.0	2.5	8.5	6.5	3433.7	61.5	4.6	0.5	27.3
	Maximum	0.7	25.1	211.5	37.9	27,496.1	937.3	105.5	3.8	179.2
	Mean (n = 36)	0.4	12.1	106.9	21.8	13,110.4	387.1	54.0	2.3	100.5
	CV (%)	49.4	52.5	62.2	40.7	48.5	65.1	62.3	41.1	42.9
Excessive or toxic [a]		5–30	15–50	10–100	20–100	>1000	400–1000	40–246	30–300	100–500

[a]: Kabata-Pendias [7].

Table 3. BCFs, from soil to roots, and TFs, from roots to stems, leaves, and fruits, of metals in *Abelmoschus esculentus* grown in soil with different sewage sludge amendment rates (mean ± standard error, n = 36).

Metal	BCF	TF_{stem}	TF_{leaf}	TF_{fruit}
Cd	0.126 ± 0.009a	0.903 ± 0.068d	2.003 ± 0.072e	2.489 ± 0.194c
Co	0.372 ± 0.029ab	0.118 ± 0.007a	0.151 ± 0.011a	0.121 ± 0.011a
Cr	1.074 ± 0.104d	0.025 ± 0.004a	0.069 ± 0.007a	0.004 ± 0.000a
Cu	1.347 ± 0.059e	0.288 ± 0.021b	0.343 ± 0.016b	0.522 ± 0.019b
Fe	0.411 ± 0.029ab	0.025 ± 0.002a	0.068 ± 0.005a	0.016 ± 0.002a
Mn	0.772 ± 0.073c	0.239 ± 0.019b	1.149 ± 0.075d	0.488 ± 0.037b
Ni	1.576 ± 0.155e	0.009 ± 0.001a	0.023 ± 0.004a	0.029 ± 0.003a
Pb	0.469 ± 0.028b	0.288 ± 0.047b	0.063 ± 0.008a	0.191 ± 0.028a
Zn	1.031 ± 0.056cd	0.452 ± 0.033c	0.496 ± 0.027c	0.642 ± 0.037b
F-value	44.1 ***	82.1 ***	334.4 ***	133.1 ***

TF_{stem}: the translocation factor of metals from *A. esculentus* roots to stems, TF_{leaf}: the translocation factor of metals from *A. esculentus* roots to leaves, TF_{fruit}: the translocation factor of metals from *A. esculentus* roots to fruits. F-values represent one-way ANOVA, df = 8. Means in the same column followed by different letters are significantly different at $p < 0.05$ according to Tukey's HSD test. ***: $p < 0.001$.

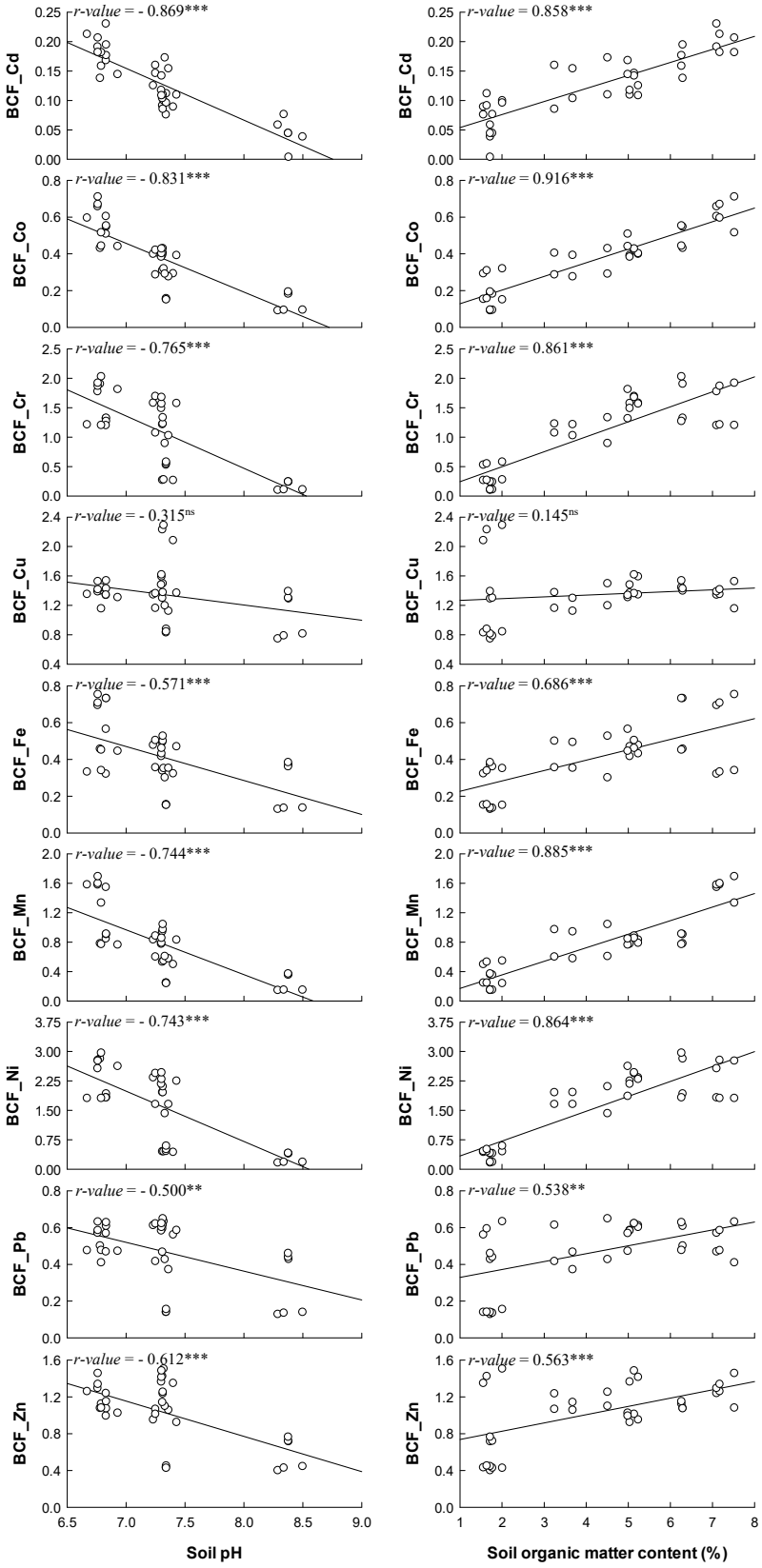


Figure 2. Simple linear correlation coefficients (r values, n = 36) between BCFs of metals in *Abelmoschus esculentus* roots and each of the soil organic matter content (%) and soil pH. **: $p < 0.01$, ***: $p < 0.001$, *ns*: not significant (i.e., $p > 0.05$).

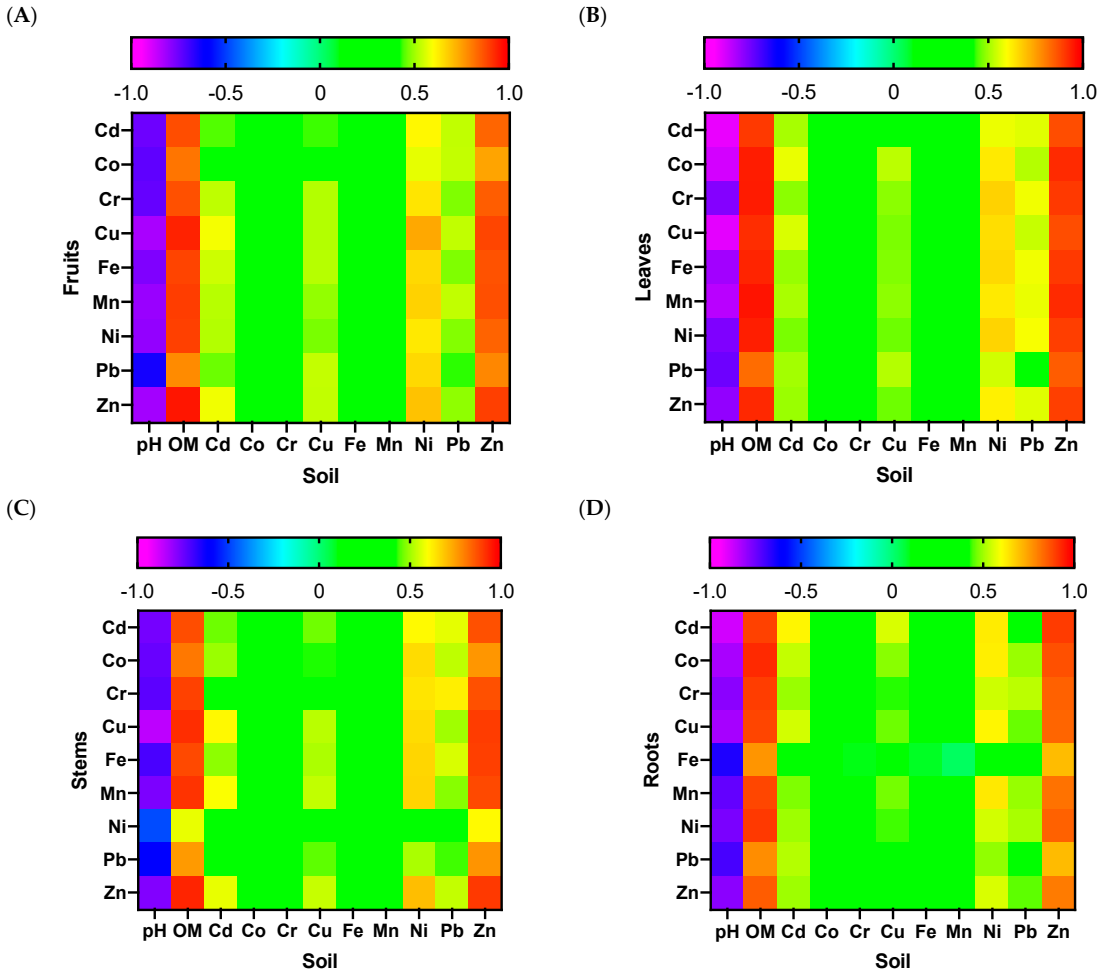


Figure 3. Pearson correlation coefficient (*r* values, *n* = 36) between the nine metal concentrations in *Abelmoschus esculentus* tissues ((**A**): Fruits, (**B**): Leaves, (**C**): Stems, (**D**): Roots) and the chemical characteristics of the soil amended with sewage sludge after harvesting *Abelmoschus esculentus* plants grown for 62 days.

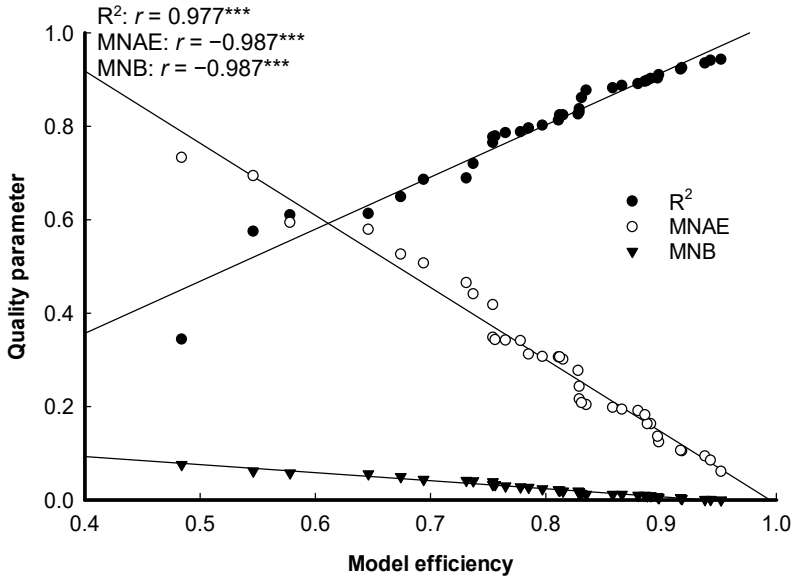


Figure 4. Simple linear correlation coefficients (*r*) between the model efficiency along the X-axis and each of R^2, *MNAE* and *MNB* along the Y-axis. ***: $p < 0.001$.

Table 4. Regression models between metal concentrations in *Abelmoschus esculentus* tissues (mg/kg) and soil metals (mg/kg), soil OM content (%), and soil pH.

Equation	R^2	*ME*	*MNAE*	*MNB*	Student's *t*-Test	
					t-Value	*p*
Fruits						
$Cd = 1.41 + 0.005 \times Cd_{soil} - 0.22 \times pH + 0.28 \times OM$	0.777	0.754	0.348	0.033	0.479	0.642
$Co = 2.05 - 0.003 \times Co_{soil} - 0.18 \times pH + 0.13 \times OM$	0.689	0.731	0.465	0.042	0.669	0.517
$Cr = 0.28 + 0.002 \times Cr_{soil} - 0.08 \times pH + 0.14 \times OM$	0.786	0.765	0.342	0.030	0.379	0.712
$Cu = 15.50 + 0.041 \times Cu_{soil} - 1.51 \times pH + 1.30 \times OM$	0.910	0.898	0.124	0.005	0.062	0.951
$Fe = 309.18 + 0.002 \times Fe_{soil} - 55.44 \times pH + 60.48 \times OM$	0.813	0.811	0.306	0.022	0.288	0.778
$Mn = 445.40 + 0.062 \times Mn_{soil} - 66.27 \times pH + 46.73 \times OM$	0.837	0.829	0.216	0.015	0.225	0.826
$Ni = 3.20 + 0.026 \times Ni_{soil} - 0.59 \times pH + 0.44 \times OM$	0.826	0.828	0.277	0.019	0.263	0.797
$Pb = 0.24 - 0.004 \times Pb_{soil} - 0.02 \times pH + 0.07 \times OM$	0.613	0.646	0.579	0.056	0.745	0.472
$Zn = 87.02 - 0.054 \times Zn_{soil} - 9.10 \times pH + 10.51 \times OM$	0.922	0.917	0.106	0.005	0.050	0.961
Leaves						
$Cd = 2.74 - 0.017 \times Cd_{soil} - 0.31 \times pH + 0.07 \times OM$	0.925	0.918	0.105	0.003	0.040	0.969
$Co = 3.53 - 0.002 \times Co_{soil} - 0.36 \times pH + 0.17 \times OM$	0.943	0.952	0.061	0.000	0.014	0.989
$Cr = 2.16 + 0.008 \times Cr_{soil} - 0.51 \times pH + 1.54 \times OM$	0.902	0.891	0.163	0.009	0.104	0.919
$Cu = 20.80 + 0.011 \times Cu_{soil} - 2.28 \times pH + 0.66 \times OM$	0.935	0.938	0.094	0.001	0.017	0.987
$Fe = 1288.85 + 0.001 \times Fe_{soil} - 153.39 \times pH + 143.20 \times OM$	0.891	0.880	0.191	0.010	0.137	0.893
$Mn = 711.96 + 0.014 \times Mn_{soil} - 86.31 \times pH + 68.59 \times OM$	0.941	0.943	0.085	0.001	0.015	0.988
$Ni = -1.56 + 0.045 \times Ni_{soil} - 0.14 \times pH + 0.67 \times OM$	0.898	0.888	0.163	0.009	0.115	0.911
$Pb = 0.40 - 0.009 \times Pb_{soil} - 0.05 \times pH + 0.03 \times OM$	0.720	0.737	0.441	0.041	0.499	0.628
$Zn = 47.34 + 0.163 \times Zn_{soil} - 6.32 \times pH + 7.13 \times OM$	0.877	0.835	0.204	0.012	0.209	0.838
Stems						
$Cd = 0.43 + 0.005 \times Cd_{soil} - 0.05 \times pH + 0.05 \times OM$	0.779	0.756	0.343	0.033	0.405	0.694
$Co = 3.77 + 0.003 \times Co_{soil} - 0.49 \times pH + 0.27 \times OM$	0.686	0.694	0.507	0.044	0.670	0.516
$Cr = 0.57 + 0.001 \times Cr_{soil} - 0.09 \times pH + 0.37 \times OM$	0.802	0.797	0.307	0.024	0.330	0.748
$Cu = 18.40 + 0.048 \times Cu_{soil} - 2.40 \times pH + 1.22 \times OM$	0.903	0.897	0.136	0.007	0.080	0.938
$Fe = -94.66 + 0.003 \times Fe_{soil} + 1.73 \times pH + 73.11 \times OM$	0.796	0.785	0.312	0.027	0.337	0.742
$Mn = 63.38 + 0.067 \times Mn_{soil} - 15.24 \times pH + 26.60 \times OM$	0.861	0.831	0.208	0.014	0.222	0.829
$Ni = 0.89 - 0.012 \times Ni_{soil} - 0.08 \times pH + 0.09 \times OM$	0.344	0.484	0.733	0.076	1.932	0.079
$Pb = -0.67 + 0.004 \times Pb_{soil} - 0.01 \times pH + 0.36 \times OM$	0.575	0.546	0.694	0.062	0.945	0.365
$Zn = 9.02 + 0.294 \times Zn_{soil} - 4.05 \times pH + 9.06 \times OM$	0.882	0.858	0.198	0.012	0.192	0.851
Roots						
$Cd = 1.02 + 0.051 \times Cd_{soil} - 0.13 \times pH + 0.05 \times OM$	0.896	0.886	0.182	0.010	0.132	0.897
$Co = 26.31 - 0.045 \times Co_{soil} - 3.05 \times pH + 2.23 \times OM$	0.887	0.866	0.194	0.012	0.160	0.875
$Cr = 197.81 - 0.002 \times Cr_{soil} - 25.85 \times pH + 23.15 \times OM$	0.824	0.815	0.301	0.019	0.266	0.795
$Cu = 47.74 + 0.052 \times Cu_{soil} - 5.16 \times pH + 2.58 \times OM$	0.830	0.829	0.243	0.018	0.228	0.824
$Fe = 19696.59 - 0.090 \times Fe_{soil} - 1722.36 \times pH + 2072.91 \times OM$	0.610	0.578	0.594	0.058	0.812	0.434
$Mn = 310.40 + 0.015 \times Mn_{soil} - 46.42 \times pH + 96.06 \times OM$	0.788	0.778	0.341	0.028	0.356	0.728
$Ni = 86.26 - 0.466 \times Ni_{soil} - 9.88 \times pH + 13.02 \times OM$	0.824	0.812	0.306	0.021	0.277	0.787
$Pb = 4.85 - 0.134 \times Pb_{soil} - 0.44 \times pH + 0.31 \times OM$	0.649	0.674	0.526	0.050	0.673	0.515
$Zn = 241.29 - 0.152 \times Zn_{soil} - 25.30 \times pH + 13.76 \times OM$	0.765	0.754	0.418	0.039	0.491	0.633

4. Discussion

The pH of the soil sludge-growing medium for *A. esculentus* was slightly alkaline at 7.3. Alkalinity is well-established as promoting the adsorption of numerous metal elements and thus diminishing their solubility in soil solutions [13,15]. The governing factors for the movement and the bioavailability of metals in soil include the adsorption and desorption characteristics of the soil [29], which are linked with the soil's OM content, pH and clay mineral content, and oxidation-reduction state [30,31]. Soil pH and the majority of the assayed metals in the component tissues of *A. esculentus* demonstrated a negative relationship. The pH of soil has been noted to play a key part in defining soil metal solubility and availability [32]. Conversely, positive associations were identified between the soil OM content and the metal concentration in the various *A. esculentus* tissues. The OM content participates in the governance of availability and movement of the metals in soils; it is a source of organic chemicals that behave as chelating agents and promote

the bioavailability of metals to plants [13]. Following the degradation of the OM content, soluble organic metal complexes are generated that enhance metal bioavailability [33]. Although, Eid et al. [1,17] suggested that sewage sludge could be a valuable fertilizer to improve growth, yield, and plant constituents of crops, sewage sludge should be utilised with caution and in controlled circumstances in order to diminish the metal accretion in soil and the subsequent metal uptake by plants.

The cumulative uptake of metallic elements by plants involves and relies on a number of soil characteristics, the components of the sewage sludge and the concentration used, the species phenology and physiology, the biochemistry related to the rhizosphere, climate characteristics, the influence of chelation, and chemical metal speciation [17,34,35]. The principal source of metal accretion and filtering in plants is thought to be the root system, which takes up metals at a slow rate, especially if they are available in significant quantity, and thus inhibits or reduces their mobility to the areal plant components [24,36]. The current research reinforced this perspective; practically all the metals were present in a higher quantity in the root systems of *A. esculentus* as opposed to in the stems, the leaves, or the fruits. If there were a root system hyper-accretion of metals, this could arise from the formation of metal complexes with sulphydryl moieties, which leads to a lower rate of metal transfer to the above-ground plant parts. A further reason why roots may demonstrate a higher metal concentration is that they are the initial plant components to be exposed to these elements within the soil [37]. In a species, such as *A. esculentus*, this is a favoured mechanism, as it suppresses the accumulation of toxic metal concentrations in the edible above-ground plant tissues, especially in the fruits that are used as foods in their young and desiccated forms. The three metals with the highest concentrations in the *A. esculentus* tissues and the soil-sludge admixture in descending ranking were Fe > Mn > Zn, implying that these were more straightforward to accumulate within the plant owing to their raised concentrations in the medium and their vital nutrient value for plant growth [34,38]. Pb and Cd demonstrated poor uptake within the plant tissues; when it occurred, these metals were identified in the plant roots [39].

When sewage sludge is added to cultivated soil, it frequently causes soil contamination as well as the accumulation and toxic impact of metals within the food chain. The concentrations of the tested metals in the sewage sludge in the present experiment, with the exception of Cd and Fe, were within proposed normal limits [7]. Furthermore, all nine metals, apart from Fe, were under the maximum safe limit in the tissues of *A. esculentus* [7]. The combination of cultivated growing media with sewage sludge may be admissible for some food crops but not all [35]. Frequent assays to confirm the metal concentrations present in such an admixture is advised to avoid the addition of toxic metals to foodstuffs.

The negative correlations identified between the soil pH and the plant metal concentration could be explained by the diminished soil availability of the metals in a basic soil solution; in contrast, a more acidic environment would enhance metal availability [13,16,40]. Conversely, the positive associations between the OM content in the soil and the concentrations of the metals in *A. esculentus* tissues could be due to the heightened mobility of metals in the soil induced by the OM content, together with their absorption by the plant [41], a result that confirms previous research [13,15,42].

Although BCF is an approximate gauge for metal uptake, it offers little information about the location properties [13]. In the present study, the BCFs were negatively and positively influenced by the soil pH and the OM content, respectively. For the five metals (i.e., Cd, Co, Fe, Mn, and Pb) for which the BCF was <1, this could reflect that the root system's ability to uptake these metals is poor, or that they are absorbed in small quantities [16]. Where the BCF was >1 (i.e., for Cr, Cu, Ni, and Zn), this implies that *A. esculentus* roots work as hyper-accumulators and could be employed as phytoremediators with respect to these elements. Apart from Cd and Mn in the leaves and Cd in the fruits, the TF was <1, indicating that the roots behave as an efficacious biological filtration system for the majority of the metals investigated, except for Cd and Mn.

Investigating the effect of soil variables on the bioavailability and the uptake of metals by plants is important for reducing the toxic impacts of these metals in agricultural ecosystems [43]. Regression models identify statistically significant soil properties that affect the uptake of metals by plants, and this process can enable a significant reduction in the transfer of these metals to the food chain and, thereby, reduce the risk to living organisms [44]. Regression models form a useful if involved strategy and enable the forecast of the metal concentrations in plant components based on soil variables (e.g., metal concentrations, pH, and OM content) [35]. Data from the current experiment indicate that the designed mathematical models relating to *A. esculentus* uptake exhibited high accuracy for the majority of the tested metals when viewed in relation to measures of model quality, i.e., R^2, *ME*, *MNAE* and *MNB*. Furthermore, it was noted that all the estimated soil variables (i.e., metal, pH, and OM content) impacted the plant uptake of the metals, which was in agreement with previous studies [42,44–46].

Since there is not much literature available relating to the establishment of regression models specifically for the absorption of metals by *A. esculentus* grown in media combined with varying sewage sludge concentrations, the obtained data were compared with studies that evaluated similar concepts using regression models pertaining to alternative crops. When judged against the tissues of *A. esculentus* in which Cd variability was 77.7–92.5%, Cd variabilities within the plant components for cucumber [1], barley [43], kidney bean [47], garden pea [48], *Corchorus olitorius* [49], *Eruca sativa* [50], and spinach [51] were 49–76%, 45–88%, 44–61%, 25–67%, 69–75%, 49–81%, and 83–88%, respectively. Bešter et al. [44] used models to measure the impact of Cd in tomato and endive, which exhibited R^2 values of 41% and 90%, respectively. R^2 parameters in relation to Cd for *Urtica dioica* as well as *Agrostis* and *Poa* species were documented as 10–47% and 31–38%, respectively [42], whereas R^2 values of 45% and 47% were obtained for lettuce and carrot, respectively [45]. Some earlier publications may have demonstrated lower parameters of R^2 for several of the models (Table A2), owing to the increased replicate frequency utilised to develop the model, which also creates significant data noise that, in turn, impacts the predictive accuracy of the affected models [52]. The degree of contaminants, the physicochemical properties of the soil at the sampling locations, the soil grade, the degree of microbial activity, the various soil derivations and mineral contents, the differing land management strategies, and the techniques utilised for sample digestion [7,53,54] may also produce the variations in R^2 seen amongst the models.

In this work, *ME* correlated positively with R^2, but negatively with *MNAE* and *MNB*, respectively. Within the plant tissues of *A. esculentus*—with certain exceptions, namely, Pb in the fruits; Ni, Pb and Co in the stems; and Fe and Pb in the roots—*MNAE* parameters were calculated to be <0.50 for all the investigated metals. If $MNAE \leq 0.50$, this has been proposed to represent consistency between the model and measured metal concentrations, implying that the model is a good fit [16]. Shaltout et al. [35] reported equivalent findings in relation to *Sorghum bicolor* cultivated in field soil that was mixed with sewage sludge.

5. Conclusions

In order to gauge the ways in which the nine investigated metals (i.e., Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb, and Zn) would be absorbed by *A. esculentus*, regression models were designed using selected soil properties as input variables. The concentrations of the nine metals in the plant tissues of *A. esculentus* demonstrated negative and positive correlations with the soil pH and OM content, respectively. The models, with the exception of those with *MNAE* parameters ≥ 0.50, exhibited high performance, efficacy, and only a modest level of inaccuracy. These data reinforce the models' feasibility for the examination of *A. esculentus* grown in sewage sludge-modified growing media. The models also provided apposite data for the majority of the tested metals in relation to the tissues of *A. esculentus*. The utilised model variables are pertinent to a spectrum of biological utilities since they can be assayed at frequent intervals. The most notable advantage of the constructed models was that they were efficient with respect to time and expense, since they reduced the dataset

size necessary to establish significant soil properties. On the other hand, the reduction in the necessary dataset size may be misleading, as only statistically significant explanatory variables are included in the regression model. Another important downside of regression models is that their predictions are valid only within the sampled interval of the explanatory variables (e.g., concentrations of metals in soil) and that the results of regression models are only reliable when the soils and plant samples present a representative statistical sample. In general, the very careful use of models within a range of site-specific parameters is necessary. The quality of models also depends on the degree of variability explained. Therefore, the authors advise that these models should be utilised with an explained variability of $R^2 > 50\%$. We encourage other researchers to use our models according to their own specific conditions. Moreover, there are also interactions between soils and other environmental properties. Thus, the model results must be interpreted while accounting for unknown variables. Additionally, more studies should investigate the uptake and associated health risks of other toxic elements (e.g., As, Hg, etc.) that may be present in the applied sewage sludge.

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Abbreviations

Abbreviation	Mean
ANOVA	Analysis of variance
BCF	Bioconcentration factor
Cd	Cadmium
Co	Cobalt
Cr	Chromium
Cu	Copper
CV	Coefficient of variation
df	Degrees of freedom
Fe	Iron
MALAS	Maximum allowable limits in agricultural soil (mg/kg)
ME	Model efficiency
Mn	Manganese
MNAE	Mean normalised average error
MNB	Mean normalised bias
MSWVC	Municipal solid waste vermicompost
NA	Not available
Ni	Nickel
n	Number of samples

OM	Organic matter content
Pb	Lead
R^2	Coefficient of determination
TF	Translocation factor
Zn	Zinc

Appendix A

Table A1. Selected chemical properties of cultivated field soil and sewage sludge used in the pot experiment of *Abelmoschus esculentus* (means ± standard error, n = 3).

Property	Cultivated Field Soil		Sewage Sludge	
	Measured Value	Normal Limit *	Measured Value	Permissible Limit **
EC (mS/cm)	0.1 ± 0.0	NA	1.4 ± 0.1	NA
pH	8.7 ± 0.0	NA	7.0 ± 0.0	NA
Organic matter content (%)	0.9 ± 0.2	NA	65.0 ± 0.9	NA
Cd (mg/kg)	2.9 ± 0.1	3	1.2 ± 0.1	20–40
Co (mg/kg)	35.5 ± 1.1	35	25.9 ± 1.3	-
Cr (mg/kg)	134.3 ± 0.7	125	176.2 ± 1.9	900
Cu (mg/kg)	15.0 ± 0.6	105	162.6 ± 2.3	1000–1750
Fe (mg/g)	42.4 ± 0.5	39.2	24.1 ± 0.5	-
Mn (mg/kg)	677.3 ± 3.2	1500–3000	560.7 ± 9.8	-
Ni (mg/kg)	68.1 ± 3.7	40	138.7 ± 3.7	300–400
Pb (mg/kg)	3.5 ± 0.4	160	671.1 ± 6.2	750–1200
Zn (mg/kg)	77.2 ± 1.9	200	667.6 ± 13.4	2500–4000

*: Kabata-Pendias [7], **: He et al. [55].

Table A2. Regression models for predicting the concentration of Cd in plants based on the concentration of Cd in soil and soil properties.

Plant	n	Model	R^2	Reference
Okra	24	$Cd_{fruit} = 1.41 + 0.005 \times Cd_{soil} - 0.22 \times pH + 0.28 \times OM\ (\%)$	77.7%	Present study
	24	$Cd_{leaf} = 2.74 - 0.017 \times Cd_{soil} - 0.31 \times pH + 0.07 \times OM\ (\%)$	92.5%	
	24	$Cd_{stem} = 0.43 + 0.005 \times Cd_{soil} - 0.05 \times pH + 0.05 \times OM\ (\%)$	77.9%	
	24	$Cd_{root} = 1.02 + 0.051 \times Cd_{soil} - 0.13 \times pH + 0.05 \times OM\ (\%)$	89.6%	
Cucumber	18	$Cd_{root} = 0.11 + 0.23 \times Cd_{soil} - 0.04 \times pH + 0.07 \times OM\ (\%)$	49%	Eid et al. [1]
	18	$Cd_{stem} = -0.56 + 0.02 \times Cd_{soil} + 0.07 \times pH + 0.03 \times OM\ (\%)$	55%	
	18	$Cd_{leaf} = -0.14–0.002 \times Cd_{soil} + 0.02 \times pH + 0.03 \times OM\ (\%)$	56%	
	18	$Cd_{fruit} = 0.74 + 0.50 \times Cd_{soil} - 0.15 \times pH + 0.17 \times OM\ (\%)$	76%	
Kidney bean	18	$Cd_{pod} = -3.576 - 0.054 \times Cd_{soil} + 0.460 \times pH + 0.099 \times OM\ (\%)$	54%	Eid et al. [47]
	18	$Cd_{leaf} = 0.930 + 0.004 \times Cd_{soil} - 0.093 \times pH - 0.002 \times OM\ (\%)$	44%	
	18	$Cd_{stem} = 1.770 - 0.037 \times Cd_{soil} - 0.174 \times pH + 0.019 \times OM\ (\%)$	51%	
	18	$Cd_{root} = 11.361 - 0.138 \times Cd_{soil} - 1.263 \times pH - 0.073 \times OM\ (\%)$	61%	
Garden pea	15	$Cd_{pod} = 4.373 - 0.052 \times Cd_{soil} - 0.480 \times pH - 0.051 \times OM\ (\%)$	60%	Eid et al. [48]
	15	$Cd_{shoot} = 1.366 + 0.003 \times Cd_{soil} - 0.133 \times pH - 0.020 \times OM\ (\%)$	25%	
	15	$Cd_{root} = -1.455 + 0.249 \times Cd_{soil} + 0.144 \times pH + 0.042 \times OM\ (\%)$	67%	
Tomato	51	$Cd_{plant} = 0.020 + 0.002 \times Cd_{soil} - 0.000008 \times Mn_{soil}$	41%	Bešter et al. [44]

Table A2. *Cont.*

Plant	*n*	Model	R^2	Reference
Cabbage	16	$Cd_{plant} = 0.007 + 0.002 \times Cd_{soil}$	44%	Bešter et al. [44]
Carrot	54	$Cd_{plant} = 0.107 + 0.017 \times Cd_{soil} - 0.00007 \times Mn_{soil}$	47%	Bešter et al. [44]
Carrot	238	$Cd_{plant} = -0.19 + 0.46 \times Cd_{soil}$	33%	dos Santos-Araujo et al. [45]
	238	$Cd_{plant} = 0.89 + 0.42 \times Cd_{soil} - 0.17 \times pH$	45%	
	238	$Cd_{plant} = 0.90 + 0.42 \times Cd_{soil} - 0.17 \times pH - 0.01 \times OM$ (%)	45%	
	238	$Cd_{plant} = 0.92 + 0.43 \times Cd_{soil} - 0.18 \times pH - 0.01 \times OM$ (%) $- 0.04 \times Clay$ (%)	45%	
Eruca sativa	18	$Cd_{leaf} = 0.326 + 0.204 \times Cd_{soil} - 0.070 \times pH + 0.136 \times OM$ (%)	81%	Eid et al. [50]
	18	$Cd_{root} = 1.518 - 0.298 \times Cd_{soil} - 0.088 \times pH + 0.067 \times OM$ (%)	49%	
Hop	13	$Cd_{plant} = 0.061 \times Cd_{soil} - 0.28 \times OM$ (%)	51%	Novotná et al. [16]
Lettuce	293	$Cd_{plant} = -0.06 + 0.39 \times Cd_{soil}$	35%	dos Santos-Araujo et al. [45]
	293	$Cd_{plant} = 1.10 + 0.44 \times Cd_{soil} - 0.18 \times pH$	42%	
	293	$Cd_{plant} = 1.35 + 0.48 \times Cd_{soil} - 0.18 \times pH - 0.28 \times OM$ (%)	44%	
	293	$Cd_{plant} = 1.11 + 0.39 \times Cd_{soil} - 0.14 \times pH - 0.22 \times OM$ (%) $- 0.14 \times Clay$ (%)	47%	
Chicory	29	$Cd_{plant} = 0.016 + 0.017 \times Cd_{soil}$	60%	Bešter et al. [44]
Endive	26	$Cd_{plant} = 0.089 + 0.032 \times Cd_{soil} - 0.014 \times OM$ (%)	90%	Bešter et al. [44]
Onion	35	$Cd_{plant} = 0.208 + 0.005 \times Cd_{soil} - 0.002 \times OM$ (%) $- 0.027 \times pH$	85%	Bešter et al. [44]
Potato	29	$Cd_{plant} = 0.042 + 0.007 \times Cd_{soil}$	76%	Bešter et al. [44]
Potato	17	$Cd_{plant} = -0.018 + 2.46 \times Cd_{soil} - 0.0041 \times Clay$ (%) $+ 0.036 \times Zn_{soil} + 0.021 \times$ pH:OM (%) $- 0.0056 \times Zn_{soil}$:pH $- 0.37 \times Cd_{soil}$:pH	60%	Novotná et al. [16]
Red beet	20	$Cd_{plant} = 0.017 + 0.026 \times Cd_{soil}$	67%	Bešter et al. [44]
Spinach	12	$Cd_{leaf} = 0.402 + 0.014 \times Cd_{soil} - 0.047 \times pH + 0.043 \times OM$ (%)	88%	Eid et al. [51]
	12	$Cd_{root} = 2.144 + 0.060 \times Cd_{soil} - 0.294 \times pH + 0.130 \times OM$ (%)	83%	
Corchorus olitorius	15	$Cd_{shoot} = 1.251 + 0.080 \times Cd_{soil} - 0.128 \times pH + 0.015 \times OM$	69%	Eid et al. [49]
	15	$Cd_{root} = 15.049 + 0.901 \times Cd_{soil} - 2.005 \times pH - 0.206 \times OM$	75%	
Urtica dioica	66	$\log Cd_{plant} = 0.26 + (0.24 \times \log CaCl_2\ [Cd]_{soil})$	10%	Boshoff et al. [42]
	68	$\log Cd_{plant} = -0.13 + (0.69 \times \log Cd_{soil}) - (0.87 \times \log$ clay %)	47%	
Rye grass	156	$Cd_{shoot} = 35.3 + 0.37 \times Cd_{soil} - 4.9 \times pH$	13%	Tudoreanu and Phillips [56]
Agrostis and Poa species	37	$\log Cd_{plant} = -0.56 + (0.58 \times \log Cd_{soil})$	38%	Boshoff et al. [42]
	37	$\log Cd_{plant} = 0.08 + (0.27 \times \log CaCl_2\ [Cd]_{soil})$	31%	
Maize	79	$Cd_{shoot} = 90.1 + 0.24 \times Cd_{soil} - 12.9 \times pH$	17%	Tudoreanu and Phillips [56]
Rice	33	$\log Cd_{grain} = 0.473 \times \log Cd_{soil} - 0.157 \times pH + 0.445 \times \log OM$ (g/kg) $- 0.984$	66%	Mu et al. [57]
Wheat	162	$\log Cd_{grain} = 0.28 + 0.44 \times \log Cd_{soil} - 0.18 \times pH$	49%	Adams et al. [58]
Wheat	100	$\log Cd_{plant} = -1.75 + 0.59 \times Cd_{soil} - 0.23 \times OM$ (%)	64%	Novotná et al. [16]
Wheat	14	$\log Cd_{grain} = 1.386 + \log Cd_{soil} - 0.279 \times pH$	85%	Liu et al. [59]
Barley	90	$\log Cd_{grain} = 0.04 + 0.21 \times \log Cd_{soil} - 0.23 \times pH$	22%	Adams et al. [58]
Barley	18	$Cd_{grain} = 0.161 - 0.023 \times Cd_{soil} - 0.005 \times pH + 0.012 \times OM$	88%	Eid et al. [43]
	18	$Cd_{shoot} = -0.946 + 0.012 \times Cd_{soil} + 0.118 \times pH + 0.031 \times OM$	45%	
	18	$Cd_{root} = -3.339 + 0.298 \times Cd_{soil} + 0.358 \times pH + 0.052 \times OM$	59%	

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