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Unveiling Soil Salinity and Heavy Metal Patterns in the Khorat Plateau, Thailand: Implications for Sustainable Development Goals (SDGs) Monitoring

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ABSTRACT

Strongly saline soils cover approximately 2,400 km² of the Khorat Plateau, Thailand, posing challenges for agriculture and environmental sustainability. This study aimed to characterize soil salinity and heavy metal patterns across five soil layers in both badlands and paddy fields. Soil samples were analyzed for pH, electrical conductivity (EC), salt content, and concentrations of As, Cd, Cu, Fe, Mn, Pb, and Zn. Results showed higher EC and salt percentages in badlands, while paddy fields exhibited greater levels of micronutrient metals such as Cu, Fe, Mn, and Zn, likely due to agricultural practices. Heavy metal concentrations remained below national safety thresholds, suggesting low contamination risk. Statistical analyses revealed significant correlations among salinity indicators, soil properties, and metal contents. These findings provide baseline data critical for environmental monitoring and support Sustainable Development Goals (SDGs) 2 and 15 by informing strategies for food security, sustainable land use, and soil resource conservation in salinity-affected regions.

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1. INTRODUCTION

The world has seen a sharp increase in the rate of climate change over the last 20 years, which is a result of both human activity and natural causes. The impacts of climate change directly and indirectly affect resources, especially soil resources, through an increase in surface water evaporation, thereby increasing the areal extent and level of soil salinity [1]. This rapid evaporation has led to an increase in the conductivity of mineral salts of more than 33% [2,3]. In addition, the upward flow or evaporation of water is one of the transmission factors causing certain heavy metal minerals to flow to the soil surface [4]. Soil that can move a significant amount of salts into solution, impacting plant growth and yield, is called saline soil. A soil's surface salinity provides evidence of this, as well as plants often showing symptoms of leaf burn in the dry season. The electrical conductivity (EC) of a water-saturated soil-corroding solution is usually greater than 2 dS/m at 25°C, at which point, plants suffer water shortage, and elemental sodium (Na) and chloride (Cl^-) poisoning occur.

Most of the alkaline saline land in Thailand is located on the northeastern Khorat Plateau, which covers an area of approximately 28,480 km². Strongly saline soils cover approximately 2,400 km² of the plateau, while moderately saline soils cover approximately 5,920 km², and near-saline soils approximately 20,160 km². In some areas of the Khorat Plateau, there is a salt crust on the ground surface caused by saline water from groundwater [5], and in areas with exceptionally salinized soil, water from the subsurface layer is frequently collected to create salt, sometimes known as "rock salt" or "earth salt" [6]. One of the effects of climate change is an increase in evapotranspiration [7-9], which subsequently increases the conduction of elements to the soil surface [10,11], some of which are environmental contaminants that could potentially enter the human food chain [12,13].

In addition to natural salinization processes, human activities such as agriculture, irrigation, and fertilizer application contribute to changes in soil chemistry and heavy metal dynamics in the Khorat Plateau [14,15]. Paddy fields often receive chemical and organic fertilizers that increase micronutrient metals such as Cu, Fe, Mn, and Zn [16,17]. In contrast, badland areas, characterized by severe degradation and minimal vegetation, are more influenced by natural salinity and parent material composition [6]. This study is based on the pollution cycle, where atmospheric pollutants fall to the soil's surface and dissolve in water, while other pathways include leaching from parent material and contributions from human activities such as transportation. The vertical and spatial distribution of heavy metals across these contrasting land uses, combined with salinity indicators like pH, electrical conductivity (EC), and NaCl content, can affect plant health, crop yield, and the risk of food chain [18,19]. Therefore, a comprehensive analysis of these interactions is essential to inform land management and environmental protection strategies in salinity-affected regions.

This study aims to determine the relationships between soil properties and heavy metal contents in strongly saline soils of the Khorat Plateau, Thailand. By analyzing soil profiles across five depths and comparing badlands and paddy fields, this research generates baseline data to support monitoring of food production areas, contributing to Sustainable Development Goals (SDG) 2 (Zero Hunger) and SDG 15 (Life on Land). The novelty of this study lies in its integration of salinity indicators and heavy metal patterns across land uses and depths, providing evidence for sustainable agriculture and environmental conservation.

2. METHODS

Soil samples were collected between November and December 2024 from the Khorat Plateau area of Nakhon Ratchasima province. The collection sites were divided into two land-

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use types: badlands (areas not utilized for agriculture or other farming and with low human activity) and paddy fields. The collection site locations, elevations, and land-use types are presented in **Table 1** and **Figure 1**.

Table 1. Soil sample collection site characteristics.

Site	Location		Elevation	Major	Land use
	N	E	(m)	soil type	
1	15.34655	101.82867	206	Sandy > Silt	Badland
2	15.11535	102.04048	179	Sandy > Silt	Badland
3	15.09625	102.01350	175	Sandy > Silt	Badland
4	15.50872	102.28598	189	Clay > Sandy	Paddy field
5	15.34528	102.58659	151	Clay > Sandy	Paddy field

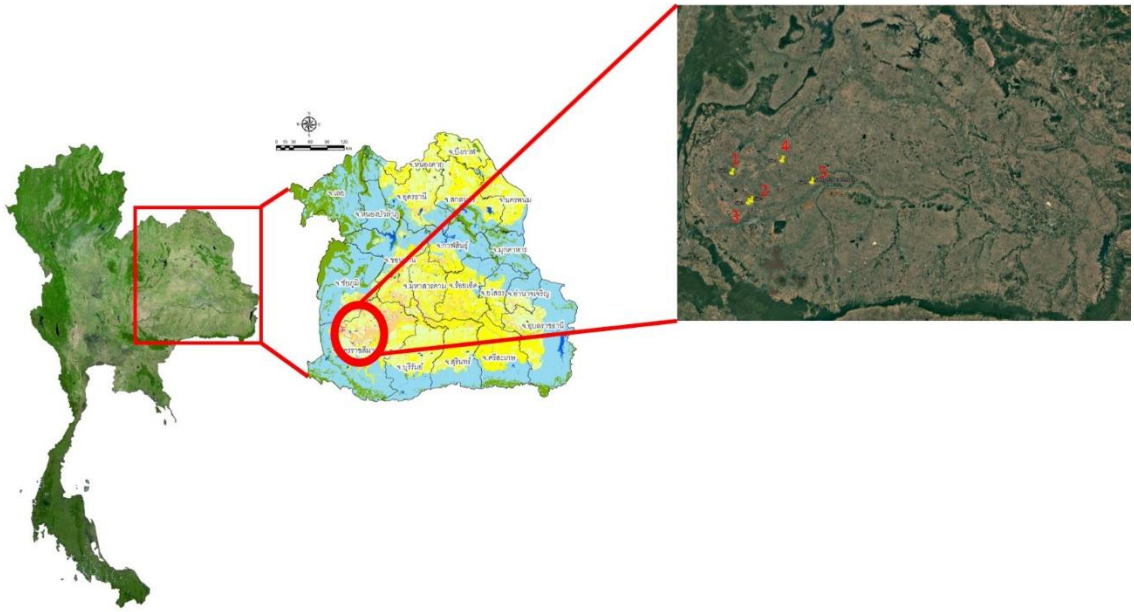

Figure 1. Location of soil sampling sites in strongly saline soil areas of the Khorat Plateau, Thailand.

2.1 Soil sampling

The soil samples were collected using a soil auger and mattock from four soil-layer depths, the topsoil (Layer 1, 0-30 cm), the subsoil (Layer 2, 31-60 cm), and the bottom layers (Layers 3-5: 61-90, 91-120, and 121-150 cm, respectively). The samples were stored in plastic bags and kept in an icebox before being transferred to the laboratory, where they were kept at -4°C in freezers before extraction and analysis.

2.2 pH, EC, and salt analysis

The soil pH, EC, and salt were tested using a solution technique. Each soil sample was dissolved in water at a ratio of 1:2 (w/v) (i.e., 5 g of soil in 10 mL of deionized water) and shaken for 30 min. The samples were allowed to settle for 30 min before the pH and salt were measured using a Hasch HQ40D portable multimeter. The EC was measured using a solution technique in an Eutech CON 700 electrochemistry instrument.

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2.3 Soil extraction and element analysis

Fifty milliliters of aqua regia (a mixture of nitric (HNO_3) (QRëC, New Zealand) and hydrochloric (HCl) (Beker Analyzed, Taiwan) acids at a ratio of 1:3) were combined with 1–2 g of soil. The mixture was then heated to about 450–500°C in a SpeedDigester K-425 BUCHI instrument (Switzerland) until completely dry. After rinsing the residue with 1% HNO_3, the sample was filtered through Whatman No. 1 paper. Next, the supernatant was poured into a 50-mL volumetric flask, and 1% HNO_3 was added. The sample was then analyzed using inductively coupled plasma optical emission spectroscopy (PlasmaQuant 9100 spectroscope, Germany). Quality assurance and quality control procedures ensured that all 30 samples, as well as their duplicates and blanks, were processed and examined according to standards in the laboratory.

2.4 Data analysis

The data were analyzed using one-way analysis of variance, and differences in the data were compared using the Tukey honestly significant difference (HSD) test at $p < 0.05$ between data components or a t-test for comparisons between the badlands and paddy fields. Principal component analysis (PCA) was used to generate a correlation matrix of components related to the arsenic (As) concentrations in the acidic soil of the study area, and a correlation analysis was performed using Pearson's correlation ($p < 0.05$). All analyses were conducted using SPSS v.22 (IBM, Armonk, NY, USA) and SigmaPlot v.12.0 (Systat, Chicago, IL, USA) software.

3. RESULTS AND DISCUSSION

3.1 Soil properties

The soil properties of the samples from the five study sites are presented in Table 2. The average pH of the topsoil in solution across the studied sites was 7.31±0.193. Site 3 had an average pH of 8.23±0.483, significantly higher than that of Site 5 (6.12±0.226) ($p < 0.5$). The 31–60-cm soil layer had an average pH of 7.09±0.125, with the 31–60-cm layers of Sites 3 and 5 having significantly higher average pH values (8.28±0.104 and 8.04±0.036, respectively) than Sites 1 and 2 ($p < 0.05$). Additionally, the pH values differed along the soil column. The topsoil (0-30 cm) and Layer 2 (31 60 cm) pH values had high variation, especially at Site 5, with significant differences ($p < 0.05$) detected between the average pH of the topsoil (6.12±0.226) and that of Layers 2–5, as presented in **Figure 2(a)**. While the pH of the saline soil was highly varied, it did not exceed 8.5. This is a typical characteristic of saline soils and arises from the distribution of Na^+ cations in the soil (Zhao *et al*., 2018).

The EC values of Sites 1-3 were significantly higher ($p < 0.05$) than those of Sites 4 and 5, as indicated in Table 2. These soil EC values appear to reflect the sites' land use and cultivation potential, as Sites 1-3 were in the badlands. At EC values higher than 4,000 mS/cm in saline soil, productivity is impacted, while at values higher than 10,000 mS/cm, plant health is deleteriously affected, and there is low to no productivity (Huang *et al*., 2017; Othaman *et al*., 2020; Yang *et al*., 2022; Delgoda *et al*., 2024). The EC also varied along the soil column, with Sites 1-3 being more stable than Sites 4 and 5, as presented in **Figure 2(b)**.

The percentage of salt in solution was found to be significantly higher ($p < 0.05$) at Site 1 than at Sites 2 and 3, and the percentage at Sites 1-3 was significantly higher ($p < 0.05$) than at Sites 4 and 5, as shown in **Table 2**. However, the percentage of salt did not differ along the soil column at Sites 1-4, while the salinity of Layers 4 (91-120 cm) and 5 (121-150 cm) at Site 5 was significantly higher ($p < 0.05$) than that of Layers 1–3. The trend in the percentage of salt in solution between soil layers is presented in **Figure 2(c)**.

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The topsoil moisture content was significantly higher ($p < 0.05$) at Sites 4 and 5 than at Site 2, as indicated in **Table 2**. Additionally, the soil moisture content was significantly lower ($p < 0.05$) in the topsoil at Site 1 than in Layers 2-5. The trend in soil moisture content between layers is presented in **Figure 2(d)**.

The bulk density of the topsoil was significantly lower ($p < 0.05$) at Sites 1 and 2 than at Sites 3 and 4, as presented in **Table 2**. Moreover, the bulk density of Layer 3 at Site 1 was significantly higher ($p < 0.05$) than that of Layers 1, 4, and 5. The trend in bulk density between layers is shown in **Figure 2(e)**.

Table 2. Soil properties of the saline soil from the Khorat Plateau, Thailand

Depth (cm)	Site 1	Site 2	Site 3	Site 4	Site 5
pH in solution					
0-30	7.12(±0.111)^{a1}	7.03(±0.050)^{a1}	8.23(±0.483)^{b1}	7.66(±0.032)^{ab1}	6.12(±0.226)^{c1}
31-60	7.18(±0.025)^{a1}	7.03(±0.132)^{a1}	8.28(±0.104)^{b1}	7.94(±0.165)^{c2}	8.04(±0.036)^{bc2}
61-91	7.32(±0.050)^{a1}	7.28(±0.065)^{a2}	8.35(±0.077)^{b1}	7.88(±0.089)^{c1}	8.04(±0.138)^{c2}
91-120	7.32(±0.061)^{abc1}	6.99(±0.047)^{ab1}	8.05(±0.052)^{ac1}	7.97(±0.052)^{ac12}	7.89(±0.673)^{ac2}
121-150	7.63(±0.175)^{a2}	7.13(±0.085)^{b12}	8.06(±0.023)^{c1}	8(±0.055)^{ac2}	7.68(±0.280)^{ac2}
EC in solution (mS/cm)					
0-30	11,648(±1,198)^{a1}	10,271(±1,150)^{a1}	4,361(±1,406)^{b1}	506(±22)^{c1}	325(±45)^{c1}
31-60	10,127(±1,322)^{a1}	8,731(±620)^{a1}	2,578(±352)^{b1}	622(±134)^{c1}	641(±32.1)^{c2}
61-91	10,925(±1,035)^{a1}	9,543(±774)^{a1}	3,141(±218)^{b1}	945(±78.1)^{c2}	626(±60)^{c2}
91-120	9,956(±1,838)^{a1}	5,711(±752)^{b2}	3,290(±632)^{bc1}	1,035(±222)^{c2}	910(±122)^{c3}
121-150	1,1416(±753)^{a1}	8,986(±1,508)^{b1}	437(±38.6)^{c1}	730(±74.5)^{c12}	1087(±164)^{c3}
Percentage of salt in solution					
0-30	0.76(±0.010)^{a1}	0.21(±0.072)^{b1}	0.2(±0.068)^{b1}	0.023(±0.005)^{c1}	0.01(±0.000)^{c1}
31-60	0.54(±0.122)^{a1}	0.09(±0.010)^{b2}	0.113(±0.030)^{b1}	0.016(±0.005)^{b1}	0.023(±0.005)^{b123}
61-91	0.606(±0.115)^{a1}	0.13(±0.026)^{b1}	0.123(±0.025)^{b1}	0.023(±0.005)^{b1}	0.02(±0.000)^{b12}
91-120	0.53(±0.210)^{a1}	0.156(±0.005)^{b1}	0.143(±0.011)^{b1}	0.046(±0.011)^{b1}	0.04(±0.010)^{b23}
121-150	0.546(±0.101)^{a1}	0.140(±0.034)^{b1}	0.140(±0.026)^{b1}	0.036(±0.011)^{b1}	0.043(±0.015)^{b23}
Percentage of soil moisture content					
0-30	12.3(±0.788)^{a1}	12(±0.114)^{a1}	15.9(±0.245)^{b1}	16.7(±0.228)^{b1}	15.7(±0.423)^{b1}
31-60	19.3(±0.559)^{a2}	17.5(±7.50)^{a1}	21.3(±9.70)^{a1}	17.8(±0.272)^{a1}	13(±0.185)^{a1}
61-91	27.7(±2.25)^{a3}	13.3(±0.403)^{b1}	17.3(±0.964)^{c1}	18.4(±0.187)^{c1}	13(±0.263)^{b1}
91-120	25.4(±2.27)^{a3}	13.3(±0.602)^{a1}	20.3(±0.343)^{a1}	17.2(±1.91)^{a1}	20.9(±1.78)^{a1}
121-150	20.9(±1.66)^{a2}	12.7(±0.700)^{ab1}	19.6(±0.710)^{a1}	24.9(±9.20)^{ac1}	19.8(±1.41)^{a1}
Bulk density (g/cm^3)					
0-30	2.43(±0.277)^{a1}	2.19(±0.222)^{a1}	4.99(±0.9035)^{b1}	4.39(±0.611)^{b1}	3.47(±1.263)^{ab1}
31-60	3.71(±0.529)^{a12}	2.71(±0.723)^{a1}	3.04(±1.63)^{a1}	4.09(±1.41)^{a1}	2.77(±0.609)^{a1}
61-91	4.88(±0.457)^{a2}	2.85(±0.854)^{b1}	2.88(±0.451)^{b1}	5.27(±0.952)^{a1}	3.23(±0.709)^{ab1}
91-120	3.05(±1.11)^{a1}	2.27(±0.294)^{a1}	4.36(±0.731)^{a1}	2.45(±0.803)^{a1}	3.14(±1.40)^{a1}
121-150	2.07(±0.606)^{a1}	1.87(±0.235)^{ab1}	3.31(±0.566)^{a1}	4.18(±1.38)^{ac1}	3.05(±0.957)^{a1}

Note: ^{abc} are significantly different based on raw Tukey HSD ($p < 0.05$), and ^{123} are significantly different based on column Tukey HSD ($p < 0.05$).

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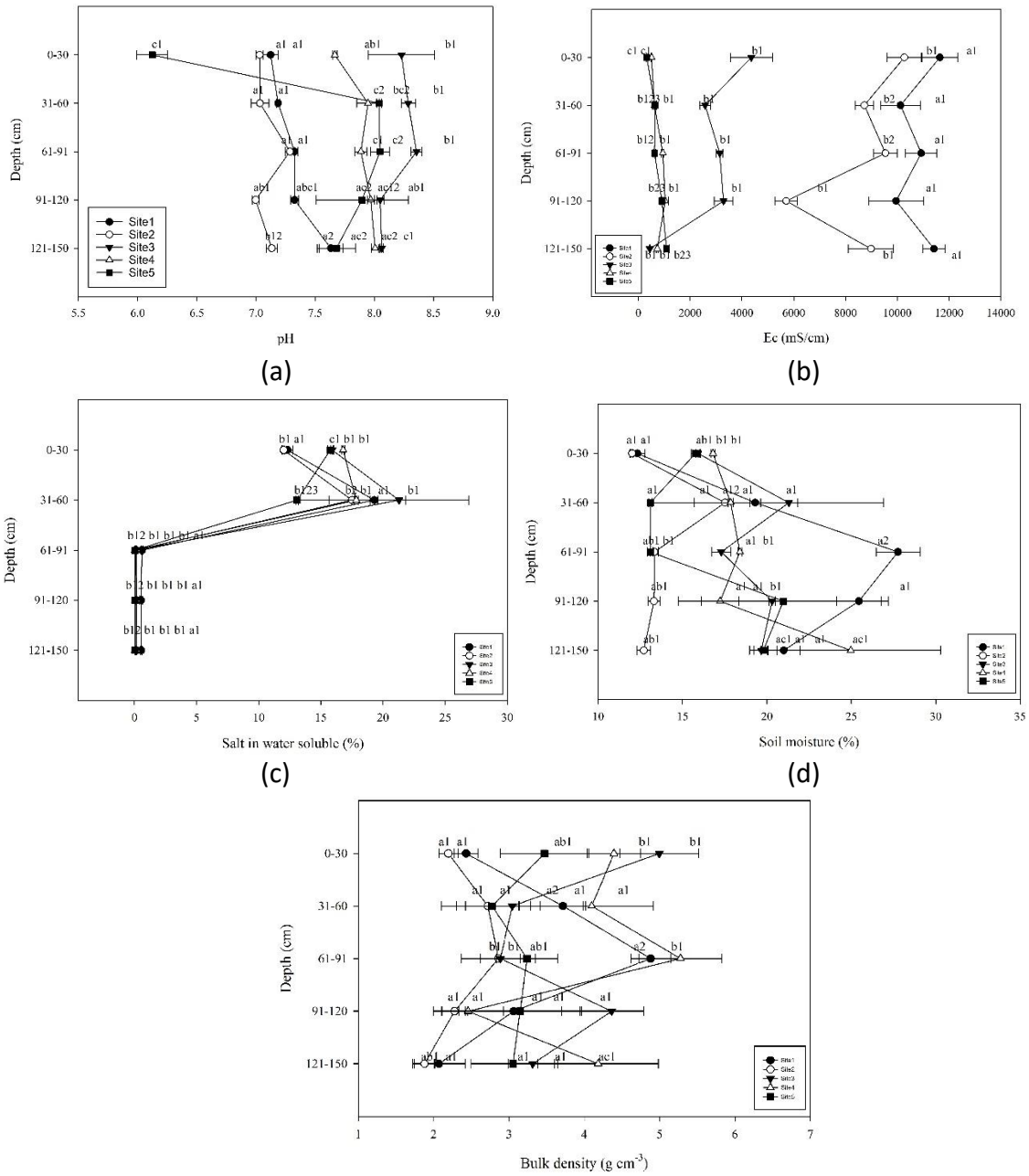

Figure 2. Trends in the properties of saline soils from the Khorat Plateau, Thailand: (a) pH; (b) EC; (c) percentage of salt in solution; (d) percentage of soil moisture content; and (e) bulk density

3.2 Sodium Fraction in Soil

Sodium is the main cause of saline soil, and its dilution and infiltration determine the distribution of saline soil zones [20]. Differences in the Na fraction between the badlands (Sites 1-3) and paddy fields (Sites 4 and 5) were subjected to t-tests. The results showed that the average Na content of the topsoil in the paddy fields (1,930 mg/kg) was significantly higher ($p < 0.05$) than that in the topsoil of the badlands (699 mg/kg). By contrast, the Na content of Layers 4 and 5 in the badlands was significantly higher ($p < 0.05$) than that in the same layers of the paddy fields, as shown in **Figure 3(a)**. Moreover, the Na content of the saline soil in Layers 1–3 of Sites 3 and 4 was significantly higher ($p < 0.05$) than that of the corresponding layers at Sites 1, 2, and 5, as presented in **Table 3**. In the soil column, the Na content differed

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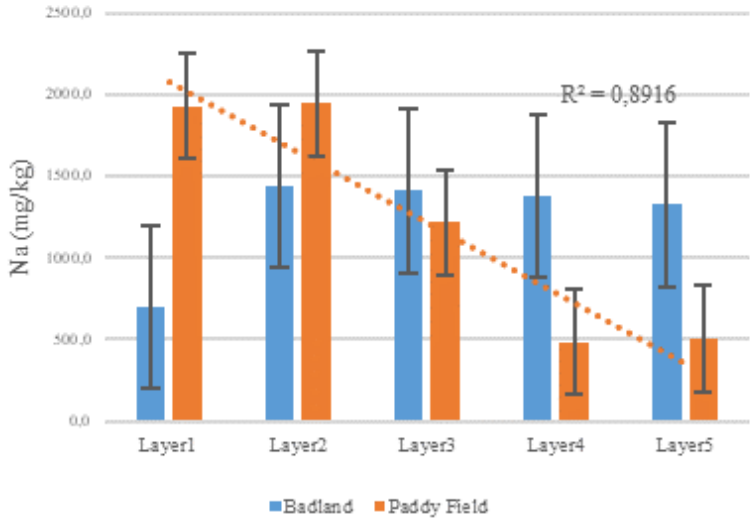
greatly between Layers 2, 3, and 4 of Site 4 and slightly between Layers 4 and 5 of Site 5, as shown in **Figure 3(b)**.

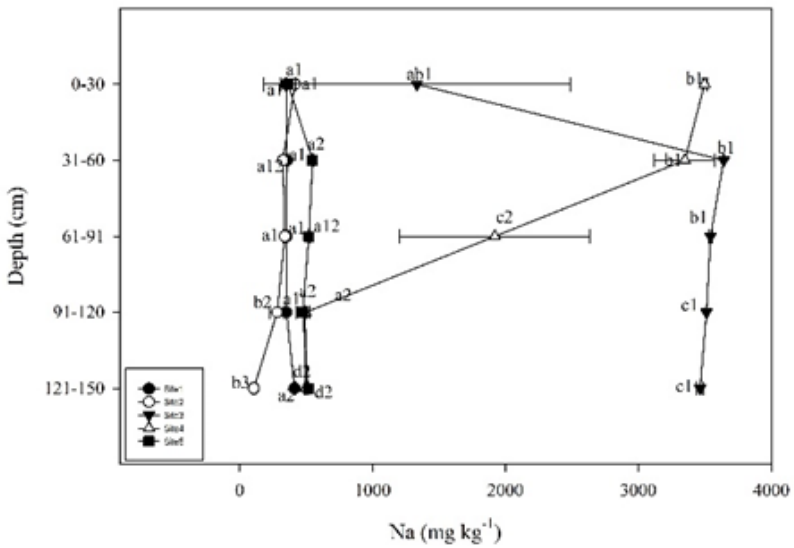
Table 3. Na fraction in the soil samples (mg/kg)

Depth (cm)	Site 1	Site 2	Site 3	Site 4	Site 5	Average
0–30	350(±7.66)^{a1}	414(±0.000)^{a1}	1,333(±1,999)^{ab1}	3,497(±30.5)^{b1}	363(±98.8)^{a1}	1,191(±1,464)
31–60	357(±7.13)^{a1}	325(±0.259)^{a12}	3,641(±4.16)^{b1}	3,350(±395)^{b1}	547(±5.72)^{a2}	1,644(±1,576)
61–91	352(±8.24)^{a1}	339(±20.8)^{a1}	3,542(±22.4)^{b1}	1,920(±1,241)^{c2}	519(±9.35)^{a12}	1,334(±1,378)
91–120	351(±1.74)^{a1}	281(±93.1)^{b2}	3,512(±1.15)^{c1}	492(±7.10)^{a2}	474(±82.1)^{a12}	1,022(±1,292)
121–150	411(±3.30)^{a2}	105(±21.3)^{b3}	3,464(±39.8)^{c1}	495(±9.70)^{d2}	515(±1.02)^{d12}	998(±1,285)

Note: ^{abc} are significantly different based on raw Tukey HSD ($p < 0.05$), and ^{123} are significantly different based on column Tukey HSD ($p < 0.05$).



(a)



(b)

Figure 3. Trends in the Na fraction of saline soils from the Khorat Plateau, Thailand: (a) comparison of the Na fraction between the badlands and paddy fields; (b) trend in Na fractions between different soil layers.

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3.3 Heavy metal contents in saline soil

The heavy metal contents detected in this study were As, cadmium (Cd), copper (Cu), iron (Fe), manganese (Mn), lead (Pb), and zinc (Zn). The concentrations of these elements in the soil are presented in **Table 4**. The element with the highest concentration in the topsoil was Fe (389±682 mg/kg), followed by Mn (231±135 mg/kg), Zn (6.60±3.38 mg/kg), Cu (6.28±5.48 mg/kg), Cd (5.73±6.62 mg/kg), Pb (2.65±1.12 mg/kg), and As (1.13 ± 0.439 mg/kg). Detailed curves for the quantity of heavy metals in each soil depth layer are shown in **Figures 4-10** for As, Cd, Cu, Fe, Mn, Pb, and Zn, respectively.

The As concentrations were highest in the subsoil (31-60 cm), and were significantly higher at Site 4 than at Sites 1–3 ($p < 0.05$). Additionally, at Site 4, the quantity of As in the subsoil was significantly higher than in the other layers ($p < 0.05$), as shown in **Figure 4**.

The average Cd concentration in the topsoil was highest at Site 4 (14.9±0.007 mg/kg) (significantly higher ($p < 0.05$) than at Sites 1 and 2), while that in the subsoil of Site 4 was 18.9(±4.49) mg/kg. Additionally, the Cd concentrations in Layers 4 and 5 (91-120 and 121-150 cm, respectively) of Site 3 were significantly higher than those in the equivalent layers at Sites 1, 2, 4, and 5 ($p < 0.05$). The Cd concentration was stable along the entire soil column of Site 1, as shown in **Figure 5**.

The Cu concentration in the topsoil was highest at Site 3, averaging 13.4 (± 7.90) mg/kg, significantly higher ($p < 0.05$) than at Sites 1, 2, and 5. However, in Layer 2, the highest Cu concentration was found at Site 4, averaging 13.4 (± 1.64) mg/kg, significantly higher ($p < 0.05$) than at Sites 1–3. Along the soil column, there was a decreasing trend in Cu concentration, as presented in **Figure 6**.

The Fe concentration was highest in Layer 4 of Site 1, averaging 1,862(±127) mg/kg, significantly higher ($p < 0.05$) than at Sites 3-5. This element showed an increasing trend along the soil column (**Figure 7**).

The Mn concentration in the topsoil was highest at Site 2, averaging 401(±77.9) mg/kg, significantly higher ($p < 0.05$) than at Sites 3-5. However, the overall Mn concentration was highest in Layer 3 of Site 5 and tended to vary along the soil column (**Figure 8**).

The Pb concentration was highest in Layer 5 of Site 3, averaging 15.6(±6.65) mg/kg, significantly higher ($p < 0.05$) than at Sites 1, 2, and 5. The Pb concentration tended to increase downward in the soil column, as shown in **Figure 9**.

The Zn concentration in the topsoil was the lowest at Site 5, averaging 1.12(±0.060) mg/kg (significantly lower ($p < 0.05$) than at Sites 1-4) and the highest in Layer 3 of Site 5, averaging 131 (± 71.3) mg/kg, which was significantly higher ($p < 0.05$) than at Sites 1-4. The Zn concentration tended to increase downward in the soil column, as presented in **Figure 10**.

Notably, the heavy metal contents in the saline soil at the study sites did not exceed the soil quality standards of the Pollution Control Department in 2021. The soils met the standard of quality for residential and agricultural areas in Thailand, staying below the value (Value A) that indicates the maximum level above which it is not possible to ensure the sustainable quality of sandy or clay soil, according to the Food and Agriculture Organization of the United Nations in 2001.

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Table 4. Heavy metal contents in each soil layer of the study sites.

	Heavy metal content in soil (mg/kg)						Standard
Layer/depth (cm)	**Site 1**	**Site 2**	**Site 3**	**Site 4**	**Site 5**	**Average**	**(mg/kg)**
As							
0–30	1.59(±0.912)^{a1}	1.02(±0.101)^{a1}	0.885(±0.085)^{a1}	1.02(±0.034)^{a1}	1.16(±0.237)^{a1}	1.13(±0.439)	25*
31–60	1.13(±0.047)^{a1}	1.03(±0.020)^{a1}	1.23(±0.352)^{ab1}	3.13(±0.619)^{b2}	2.65(±1.42)^{ab1}	1.83(±1.08)	6**
61–91	1.04(±0.050)^{a1}	1.15(±0.089)^{a1}	1.06(±0.065)^{a1}	1.01(±0.043)^{a1}	0.922(±0.335)^{a1}	1.03(±0.156)	4***
91–120	1.16(±0.025)^{a1}	1.10(±0.122)^{a1}	1.02(±0.174)^{a1}	1.02(±0.056)^{a1}	1.02(±0.052)^{a1}	1.06(±0.105)	5****
121–150	0.928(±0.019)^{a1}	1.36(±0.570)^{a1}	1.05(±0.338)^{a1}	1.11(±0.346)^{a1}	1.20(±0.226)^{a1}	1.13(±0.332)	
Cd							
0–30	0.042(±0.006)^{a1}	0.052(±0.001)^{a1}	10.4(±6.19)^{b1}	14.9(±0.007)^{bc1}	3.14(±0.766)^{ab1}	5.73(±6.62)	762*
31–60	0.044(±0.006)^{a1}	2.62(±0.052)^{a2}	14.9(±0.016)^{b1}	18.9(±4.49)^{b1}	1.99(±0.937)^{a1}	7.62(±8.04)	67**
61–91	0.032(±0.013)^{a1}	3.76(±0.668)^{ab3}	14.9(±0.066)^{b1}	15.9(±0672)^{b1}	16.0(±11.9)^{b1}	10.1(±8.41)	0.08***
91–120	0.033(±0.016)^{a1}	3.63(±0.129)^{b3}	14.9(±0.026)^{c1}	1.82(±0.004)^{a2}	5.35(±2.08)^{b1}	5.16(±5.45)	0.2****
121–150	0.049(±0.004)^{a1}	3.42(±0.015)^{b23}	15.2(±0.251)^{c1}	1.87(±0.047)^{d2}	3.09(±0.010)^{e1}	4.72(±0.004)	
Cu							
0–30	3.16(±0.396)^{a1}	2.10(±0.026)^{a1}	13.4(±7.90)^{b1}	8.95(±0.240)^{ab1}	2.73(±0.779)^{a1}	6.28(±5.48)	35040*
31–60	2.94(±1.24)^{a1}	1.19(±0.212)^{a2}	7.05(±0.898)^{b1}	13.4(±1.64)^{c2}	4.56(±1.75)^{ab2}	5.84(±4.54)	2920**
61–91	3.19(±0.559)^{a1}	0.441(±0.371)^{b3}	7.73(±0.476)^{c1}	6.53(±0.267)^{d3}	9.22(±1.04)^{c3}	5.42(±3.33)	4***
91–120	2.63(±0.109)^{a1}	0.584(±0.117)^{a3}	7.18(±0.954)^{b1}	1.93(±0.558)^{a4}	7.28(±2.44)^{b32}	3.92(±3.05)	19****
121–150	2.22(±0.036)^{a1}	0.812(±0.032)^{a2}	10.4(±2.87)^{b1}	1.94(±0.630)^{a4}	6.66(±1.18)^{b123}	4.41(±3.91)	
Fe							
0–30	967(±1,137)^{a1}	591(±1,017)^{a1}	221(±166)^{a1}	55.1(±79.2)^{a1}	109(±75.9)^{a1}	389(±682)	—
31–60	51.5(±21.6)^{a12}	40(±52.8)^{a1}	9.55(±6.40)^{a1}	2.69(±3.88)^{a1}	2.12(±2.77)^{a1}	21.1(±30.4)	—
61–91	53.8(±48.0)^{a12}	480(±539)^{a1}	662(±525)^{a1}	457(±758)^{a1}	2,412(±2,517)^{a1}	813(±1,340)	—
91–120	1,826(±127)^{a13}	1,013(±984)^{ab1}	110(±67.3)^{b1}	206(±321)^{b1}	111(±152)^{b1}	653(±806)	—
121–150	77(±77.4)^{a12}	2,160(±3,675)^{a1}	3,091(±2,893)^{a1}	1,699(±1,175)^{a1}	3,615(±1,850)^{a1}	2,128(±2,329)	
Mn							
0–30	284(±46.5)^{a1}	401(±77.9)^{a1}	263(±41.6)^{bc1}	180(±55.7)^{c1}	26.1(±4.73)^{d1}	231(±135)	19,640*
31–60	13.8(±46.5)^{a2}	90.1(±50.2)^{b1}	8.84(±10.7)^{a1}	1.43(±1.25)^{a1}	0.594(±0.436)^{c1}	22.9(±40.1)	1,710**
61–91	45(±38.25)^{a2}	317(±163)^{a1}	871(±271)^{a2}	420(±1,815)^{a1}	1,936(±1,155)^{b2}	718(±827)	—
91–120	513(±76.4)^{a3}	434(±327)^{a1}	249(±223)^{a1}	230(±28.5)^{a1}	219(±128)^{a1}	329(±203)	—
121–150	34.6(±23.8)^{a2}	388(±221)^{a1}	314(±193)^{a1}	501(±569)^{a1}	108(±37.6)^{a1}	269(±302)	

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Table 4 (continue). Heavy metal contents in each soil layer of the study sites.

	Heavy metal content in soil (mg/kg)						Standard
Layer/depth (cm)	**Site 1**	**Site 2**	**Site 3**	**Site 4**	**Site 5**	**Average**	**(mg/kg)**
Pb							
0–30	3.35(±1.72)^{a1}	3.05(±1.92)^{a1}	2.67(±0.470)^{a1}	2.18(±0.049)^{a1}	2.01(±0.025)^{a1}	2.65(±1.12)	800*
31–60	1.94(±0.025)^{a1}	2.61(±2.97)^{a1}	5.14(±6.02)^{a12}	1.44(±0.111)^{a12}	1.26(±0.020)^{a1}	2.48(±2.93)	400**
61–91	1.11(±0.136)^{a2}	2.31(±1.62)^{a1}	7.06(±2.24)^{a12}	2.80(±4.34)^{a1}	7.61(±9.51)^{a1}	4.18(±4.92)	13***
91–120	7.58(±0.345)^{a3}	9.54(±7.23)^{a1}	2.26(±1.07)^{a1}	3.76(±1.08)^{a23}	7.24(±6.23)^{a1}	6.08(±4.58)	23****
121–150	4.06(±0.352)^{a1}	4.16(±3.30)^{a1}	15.6(±6.65)^{b2}	6.68(±3.12)^{ab3}	6.61(±1.61)^{a1}	7.82(±5.39)	
Zn							
0–30	7.76(±0.637)^{a1}	7.67(±2.59)^{a1}	9.46(±1.43)^{a1}	7.01(±3.10)^{a1}	1.12(±0.060)^{b1}	6.60(±3.38)	—
31–60	0.826(±0.045)^{a2}	15.2(±9.06)^{b1}	8.82(±5.73)^{ab1}	5.24(±0.376)^{ab1}	4.72(±0.027)^{ab1}	6.97(±6.45)	—
61–91	4.79(±0.153)^{a4}	7.53(±4.95)^{a1}	38.5(±5.03)^{a2}	27.8(±9.64)^{a2}	131(±71.3)^{b2}	41.9(±55.2)	—
91–120	47.1(±1.25)^{a3}	21.8(±27.5)^{ab1}	6.26(±1.80)^{b1}	8.57(±0.810)^{b12}	15.7(±8.01)^{ab1}	19.9(±18.6)	—
121–150	3.90(±0.240)^{a4}	8.59(±1.47)^{a1}	22.5(±12.6)^{a12}	18.5(±12.6)^{a12}	9.81(±0.467)^{a1}	12.6(±9.80)	

Note:

^{abcd} are significantly different based on raw Tukey HSD ($p < 0.05$), and ^{123} are significantly different based on column Tukey HSD ($p < 0.05$).

*Soil quality standard for residential areas in Thailand.

**Soil quality standard for agricultural areas in Thailand.

***Target (Value A) soil standard—the maximum level above which it is not possible to ensure the sustainable quality of sandy soil.

****Target (Value A) soil standard—the maximum level above which it is not possible to ensure the sustainable quality of clay soil.

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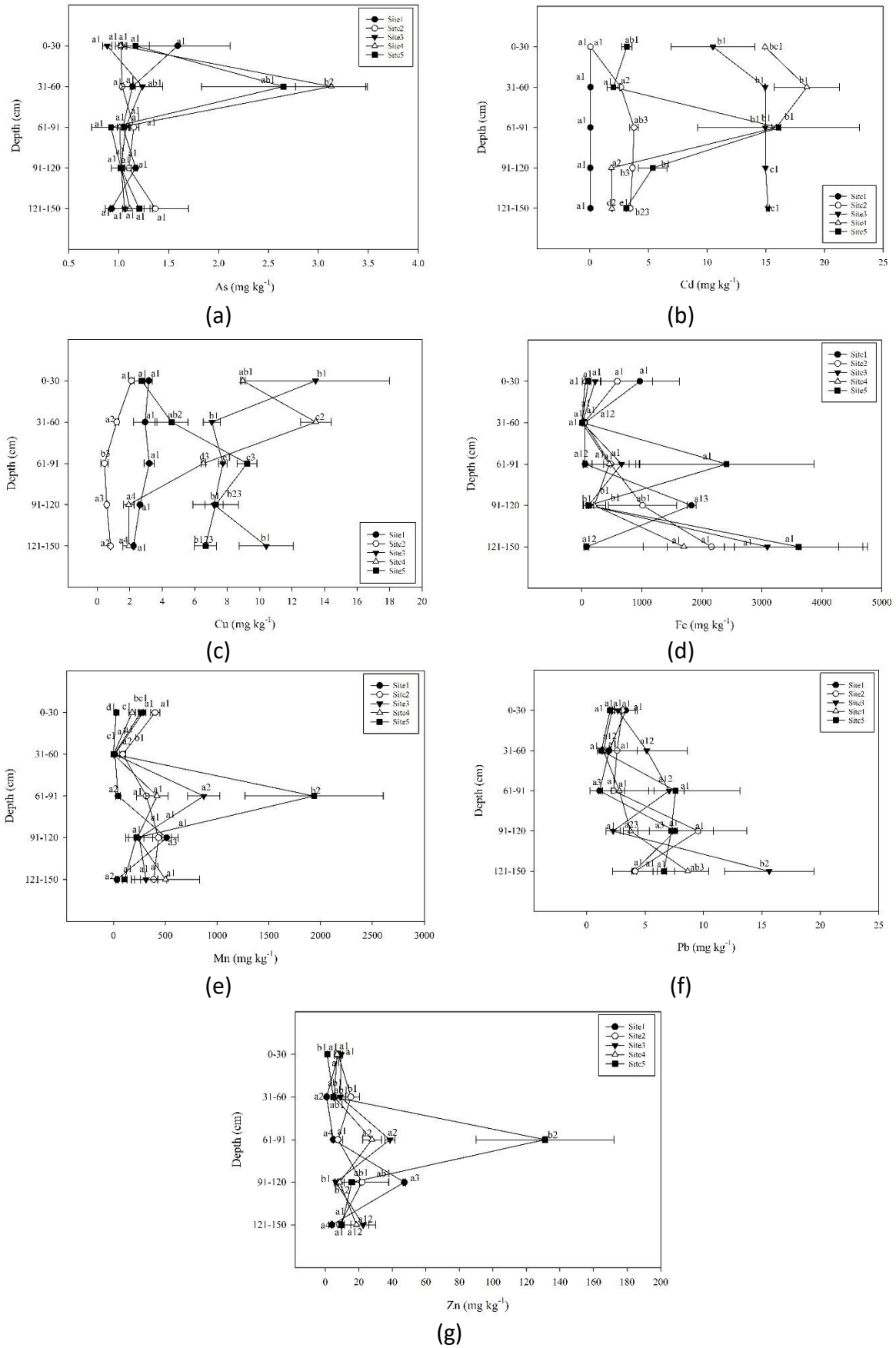

Figure 4. Quantity of heavy metals in each soil depth layer: (a) As; (b) Cd; (c) Cu; (d) Fe; (f) Pb; and (g) Zn

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3.4 Correlations between components of saline soils from the Khorat Plateau

A test for relationships among the 15 measured soil sample components was performed using Spearman's correlation coefficient (**Table 5**). The two land-use types were positively correlated with the Na, Cu, Fe, Pb, Cu, and Zn concentrations ($p < 0.01$) and negatively correlated with EC and the percentage of NaCl in solution ($p < 0.01$). The percentage of NaCl in solution was positively correlated with EC (r=0.826; $p < 0.01$) and Zn concentration (r=0.717; $p < 0.01$), but negatively correlated with the Cd, Pb, Na, Cu, Fe ($p < 0.01$), and Zn ($p < 0.05$) concentrations. However, the Na concentration was positively correlated with land use, pH, and the Cd, Cu, Fe, Pb, Mn, and Zn concentrations ($p < 0.01$), as well as with the soil moisture content and bulk density of the soil ($p < 0.05$). The Na concentration was also negatively correlated with EC (r=–0.522; $p < 0.01$) and the percentage of NaCl in solution (r=–0.395; $p < 0.01$).

Table 5. Correlation of components of the saline soils from the Khorat Plateau

	Land use	**Depth**	**pH**	**EC**	**% Salt**	**% Soil moisture**	**Bulk density**	**Na**
Land use	1.000	—	—	—	—	—	—	—
Depth	—	1.000	—	—	—	—	—	—
pH	—	—	1.000	—	—	—	—	—
EC	-0.747**	—	-0.420**	1.000	—	—	—	—
% Salt	-0.851**	—	-0.233*	0.826**	1.000	—	—	—
% Soil moisture	—	0.375**	0.306**	—	—	1.000	—	—
Bulk density	—	—	0.277*	-0304**	—	0.533**	1.000	—
Na	0.319**	—	0.676**	-0522**	-0395**	0.268*	0.263*	1.000
Cd	—	—	0.496**	-0540**	-0467**	—	0.235*	0.552**
Cu	0.314**	—	0.594**	-0491**	-0324**	0.272*	0.347**	0.706**
Fe	0.383**	—	0.365**	-0409**	-0302**	—	—	0.548**
Pb	0.536**	—	—	-0438**	-0448**	—	—	0.336**
Mn	—	—	0.536**	-0367**	—	0.366**	0.326**	0.641**
Zn	—	—	0.463**	-0.400**	-0274*	0.251*	0.251*	0.466**
As	—	—	—	—	—	-0344**	-0.407**	—
	Cd	**Cu**	**Fe**	**Pb**	**Mn**	**Zn**	**As**	
Cd	1.000	—	—	—	—	—	—	—
Cu	0.561**	1.000	—	—	—	—	—	—
Fe	—	0.713**	1.000	—	—	—	—	—
Pb	—	0.578**	0.682**	1.000	—	—	—	—
Mn	—	0.615**	0.571**	0.426**	1.000	—	—	—
Zn	0.359**	0.607**	0.482**	0.574**	0.717**	1.000	—	—
As	—	—	—	—	—	—	1.000	—

Note: * two-tailed $p < 0.05$; ** two-tailed $p < 0.01$; Land use = badland, paddy field; Depth = soil layer (0–30, 31–60, 61–90, 91–120, 121–150 cm); % Salt = percentage of NaCl in solution.

3.5 Factor analysis

Fifteen components were used as parameters in the PCA. Before this test, the soil properties and heavy metal contents of the samples were tested using the Kaiser–Meyer–Olkin (KMO) and Bartlett tests. The KMO measure of sampling adequacy was 0.575, and there was a significant difference between the eigenvalues ($p < 0.001$), as presented in **Table 6**. The PCA found five principal components (PCs), three of which had eigenvalues over 1.5 and explained 58.236% of the total variance in the dataset (**Table 7** and **Figure 11**). Variance of

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over 10% was found for PC1, PC2, and PC3. The most important contributors to PC1 were EC and Cd, with factor loadings of -0.800 and 0.794, respectively. For PC2, the factor loading of soil moisture content was 0.610, and that of land use was -0.619. For PC3, the factor loading of Zn was 0.527, and that of bulk density was -0.599.

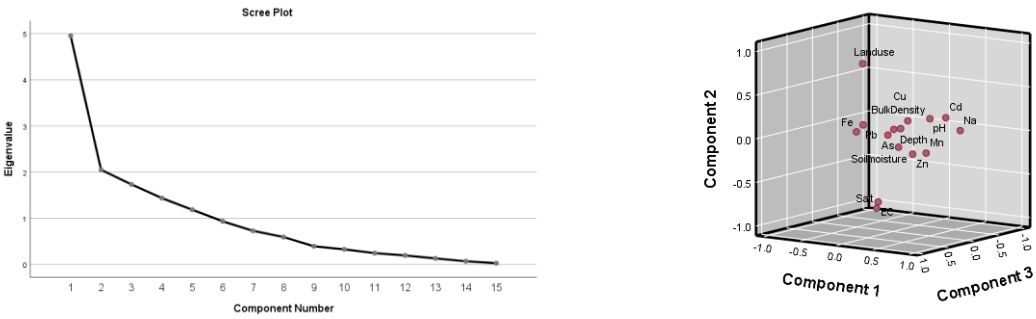
Table 6. Results of the KMO and Bartlett tests of soil properties and heavy metal contents of the saline soils from the Khorat Plateau

KMO measure of sampling adequacy	0.575
Bartlett's test of sphericity approx. chi-square	745.041
df	105
Sig.	0.000

Table 7. Results of the PCA of the statistical significance of the soil properties and heavy metal contents of the saline soils from the Khorat Plateau

PC	Component		
	1	**2**	**3**
% Variance	33.015	13.667	11.554
Cumulative %	33.015	46.682	58.236
Eigenvalue	4.95	2.05	1.73
Land use	0.478	-0.619	-0.417
pH	0.669	0.221	0.025
EC	-0.800	0.369	0.234
% Salt	-0.580	0.546	0.201
% Soil moisture	0.161	0.610	-0.273
Bulk density	0.384	0.369	-0.599
Na	0.684	0.368	0.044
Cd	0.794	0.171	-0.045
Cu	0.768	0.029	0.027
Fe	0.481	-0.308	0.399
Pb	0.655	-0.304	0.218
Mn	0.549	0.378	0.387
Zn	0.606	0.213	0.527
As	-0.320	-0.363	0.482
Depth	0.082	0.060	0.397

Note: % Salt = percentage of NaCl in solution; Depth = layer within the soil column.



(a) (b)

Figure 11. Results of the PCA for soil properties and heavy metal contents of the saline soils from the Khorat Plateau: (a) eigenvalue of the components in the principal analysis; and (b) loading of the PC components.

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3.6 Land-use influences on heavy metal contents in the saline soils of the Khorat Plateau

The studied land-use types were badlands and paddy fields, between which the following were compared:

(i) soil properties, including soil pH, EC, percentage of salt in solution, percentage of soil moisture content, and bulk density; and

(ii) heavy metal contents, including Cd, Cu, Fe, Pb, Mn, Zn, and As.

The pH and bulk density were significantly higher in the paddy fields than in the badlands ($p < 0.01$), while the percentage of soil in solution and the EC were significantly higher in the badlands than in the paddy fields ($p < 0.01$), as presented in **Table 8**. The concentrations of Fe, Cu, Pb, Mn, and Zn were significantly higher in the paddy field soils than in the badland soils ($p < 0.01$), while the as concentrations were significantly higher in the badlands than in the paddy fields ($p < 0.05$).

It should be noted that some heavy metals, such as Cu, Fe, Mn, and Zn, are micro-elements that are important for plants [16,21,22]. The elemental contents of the paddy field soils were likely higher than those in the badlands due to aeration caused by plowing, the redox conditions of raw material in the paddy fields resulting in differences in the metal fraction [18,23]. In addition, heavy metals can originate from chemical fertilizers and other agricultural chemicals [14]. However, the heavy metals in soil may also be of natural origin, depending on the parent material, such as rare-earth metals [15]. The acceptable background levels of heavy metals in the soils of Thailand are 26 mg/kg As, 1.7 mg/kg Cd, 41 mg/kg Cu, 55 mg/kg Pb, and 90 mg/kg Zn. The paddy field study sites had high Cd background values, suggesting that agricultural activity has resulted in increased Cd contamination of the soil.

Table 8. Comparison between soil properties and element contents of saline soils from the badlands and paddy fields of the Khorat Plateau

Indicator	Land use		Paired differences		
	Badland	Paddy field	Mean	SD	Sig. (2-tailed)
pH	7.20(±0.201)	7.72(±0.597)	–0.518	0.565	0.000
EC (mS/cm)	9,731(±1,905)	742(±254)	8,988	1,985	0.000
% NaCl in solution	0.371(±0.251)	0.302(±0.013)	0.342	0.252	0.000
% Soil moisture content	17.4(±5.98)	17.7(±5.121)	–0.324	7.46	0.813
Bulk density (g/cm^3)	2.80(±1.00)	3.60(±1.19)	–0.800	1.32	0.002
Cd (mg/kg)	1.86(±3.47)	7.77(±7.48)	–5.90	8.85	0.001
Cu (mg/kg)	2.29(±2.12)	6.99(±5.62)	–4.69	6.17	0.000
Fe (mg/kg)	205(±510)	1,391(±1,869)	–1,186	1,960	0.002
Pb (mg/kg)	2.56(±2.18)	6.95(±4.99)	–4.38	5.33	0.000
Mn (mg/kg)	127(±144)	299(±255)	–172	257	0.000
Zn (mg/kg)	6.79(±5.06)	16.3(±15.1)	–9.51	16.0	0.002
As (mg/kg)	1.48(±0.889)	1.10(±0.244)	0.386	0.899	0.025

Note: Mean differences significant at the $p < 0.05$ level.

3.7 Behavior of saline soil to heavy metal content

The indicators of saline soil include the salt content in the surface soil [19], the percentage of salt soluble in water, Na^+, and EC [24]. These indicators are related to the percentage soil moisture content and pH, which correlate with the soil element contents, especially Cu and Pb, which are in turn negatively correlated with soil salinization [25]. In **Table 5**, soil pH was positively correlated with Cd, Cu, Fe, Mn, and Zn, while EC was negatively correlated with soil pH [26,27]. The EC was also negatively correlated with Na, Cd, Cu, Fe, Pb, Mn, and Zn.

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However, the Na content and percentage of salt in solution are negatively correlated in saline soil because the percentage of NaCl in solution occurs in the form of $Na^+(aq) + Cl^-(aq)$, thus the positive correlation with EC. In addition, the Na fraction was positively correlated with soil pH, soil moisture content, and bulk density, helping explain the saline soils' characteristics.

The percentage of salt in solution in the soil column was highest in the topsoil (Layer 1, 0-30 cm) and subsoil (Layer 2, 31-60 cm), then decreased in subsequent layers, becoming increasingly stable. This is characteristic of the vertical distribution of salt through the soil column [28-30] because salt introduced to the soil surface cannot then permeate back to the lower layers [31,32]. However, we found similar patterns in the vertical distributions of As, Fe, Mn, and Zn along the soil column, with high variability in the surface layer of the soil and greater stability in concentrations with increasing depth of the soil.

3.8 Landuse and Land condition to Food Security

The results present to agricultural areas had higher accumulation of heavy metals, which are microelement of plant nutrients, such as Cu, Fe, Mn and Zn, than badland areas, because farmers used fertilizers, especially manure, to improve the soil [33,17]. However, the soil pH influences some metals, such as the Agricultural areas are found to have a pH that is higher than badlands, resulting in lower arsenic levels [34,35], and the soil moisture has an influence on soil pH together. In the relationship between the influence of soil conditions and the amount of heavy metal accumulation caused by human activities and the soil source, which has a direct relationship and influence, the results of the study help monitor the safety of important food production areas of the country.

3.9 Soil properties and Heavy metal contamination to SDG in Khorat Plateau

The soil properties and heavy metals in the Korat plateau are directly related to several SDGs, especially SDG 15, which emphasizes the conservation and sustainable management of terrestrial resources [36]. To prevent soil degradation and maintain the balance of the ecosystem, the heavy metals in the soil are mainly derived from human activities and have a complex chemical behavior, which affects the risks to the environment and human health, and the risk assessment and management are essential for the conservation of soil resources and environmental sustainability [37,38], concerning SDG 2, achieving food security and improving food security, and promoting sustainable agriculture.

4. CONCLUSION

This study revealed that strongly saline soils of the Khorat Plateau exhibit distinct variations in pH, electrical conductivity, salt content, and heavy metal concentrations across different soil depths and land use types. Badlands were characterized by higher salinity indicators, while paddy fields showed elevated levels of essential micronutrient metals such as Cu, Fe, Mn, and Zn, likely due to agricultural practices. Importantly, all heavy metal concentrations remained below national safety standards, indicating low contamination risk for agricultural production. These findings provide critical baseline data for monitoring soil health and guiding sustainable land management in salinity-affected regions. The study contributes to SDGs, especially SDG 2 and SDG 15, by supporting food security efforts and the conservation of terrestrial ecosystems in areas vulnerable to salinization and metal accumulation.

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6. AUTHORS' NOTE

The authors declare that there is no conflict of interest regarding the publication of this article. The authors confirmed that the paper was free of plagiarism.

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