

## Evaluation of Bentonite Efficiency in the Management of Lead- and Cadmium-Contaminated Soils and the Improvement of Their Physical, Chemical, and Hydrological Properties

Fatimah Marzoq Hashim <sup>1\*</sup>, Luma Abdalalah Sagban Alabadi <sup>2</sup>,

<sup>1</sup>Department of Soil Science and Water, College of Agriculture, University of Al-Qadisiyah, Iraq.

<sup>2</sup>Department of Soil Science and Water, College of Agriculture, University of Al-Qadisiyah, Iraq.

### Abstract:

This study aimed to evaluate the efficiency of bentonite mineral in the management of soils contaminated with lead (Pb) and cadmium (Cd) by reducing their mobility and improving soil physical properties. A factorial experiment was conducted including different contamination levels of lead (0, 10, 100, and 200 mg kg<sup>-1</sup>) and cadmium (0, 5, 15, and 25 mg kg<sup>-1</sup>), with two levels of bentonite application (25% and 50%), in addition to a control treatment without amendment. Several soil physical and hydrological properties were measured, including bulk density, particle density, total porosity, hydraulic conductivity, saturation percentage, field capacity, and permanent wilting point, as well as the residual concentrations of lead and cadmium in the soil. The results revealed significant differences among treatments at the 0.05 probability level. Bentonite application markedly improved soil physical properties; bulk density decreased from 1.57 g cm<sup>-3</sup> in the control treatment to approximately 1.40 g cm<sup>-3</sup> with 50% bentonite addition, while total porosity increased from 39.67% to 43.33%. Electrical conductivity decreased from 4.16 to 3.51 dS m<sup>-1</sup>, whereas saturation percentage increased from 37.87% to 46.27%, and field capacity increased from 15.57% to 21.53%. The results also demonstrated that bentonite was more effective in immobilizing lead compared with cadmium. Overall, the findings confirm that bentonite acts as an effective physical amendment in the management of Pb- and Cd-contaminated soils, as it enhances soil structure and hydrological properties while simultaneously reducing heavy metal mobility and associated environmental risks.

**Keywords:** Bentonite, Lead and cadmium pollution, Soil physical properties, Heavy metal immobilization stabilization, Water retention characteristics.

### Introduction

Heavy metal contamination in soils is considered one of the most serious environmental challenges threatening modern agricultural systems, as it reduces soil fertility and poses significant risks to environmental sustainability and human health. Among toxic elements, lead (Pb) and cadmium (Cd) are of particular concern due to their persistence, non-biodegradable nature, and high toxicity, in addition to their ability to accumulate in soil-plant systems and subsequently enter the food chain

, leading to a reduction in soil fertility and posing direct threat on human health and environment. Of heavy metals, both lead (Pb) and cadmium (Cd) is most widely distributed and are toxicants since they are non-biodegradable, have a high toxicity rate and can accumulate in soil as well as in plants; thereafter gain access to the food chain (1) (2)

. This calls for the development and application of viable options that can be used to manage soils polluted with these elements.

Pb and Cd in the soil are derived from various sources.[3] highlighted that industrial operations, mining tailings, production of phosphate fertilizers, and irrigation with contaminated water are the most common means by which these metals enter into soils. These elements accumulate, resulting in changes in soil chemical and physical status, such as lowered Soil pH, increased soil EC value and modifications of the soil structure and pore system. Such alterations are detrimental to the productivity of soil and to environmental sustainability.

These metals could have mobility and bioavailability are not only directly related to its total content, but also significantly depends on soil physical and chemical characteristics such as bulk density, porosity, hydraulic conductivity and cation exchange capacity. Any change in these properties may promote the leaching of heavy metals, or increase plant availability, which lead to higher environmental risks[4].

Soil amendments have been employed as sustainable alternative for the treatment of contaminated soil in this scenario. discussed that these amendments constituted an environmentally and economically sustainable alternative to conventional removal techniques since, compared to the classic ones, they have been found capable of immobilizing pollutants in soils without negatively impacting on soil structure. Among these materials, bentonite was extensively

studied because of its unique physical and chemical feature [5] .

Bentonite has such a large specific surface area, abundant negative charges and strong cation exchange capacity that can readily adsorb and immobilize the heavy metal ions.[6] had verified the reorganization of soil particles

It has also been postulated by some researchers that enhancement of soil physical properties is a key consideration in minimizing heavy metal mobility in soil profile. A decrease in hydraulic conductivity and an increase in water holding capacity are able to retard the flow of water, which subsequently restricts leaching transport. [7] also reported that use of bentonite improved some soil hydraulic parameters and increased water retention capacity, promoting lower mobility of Pb and Cd and lowering the hazard concerning groundwater pollution.

On the other hand, [8] recorded distinct behaviour of Pb and Cd in clay treated soils. Lead is typically more immobilized as compared to cadmium, because it has higher sorption coefficient in and stronger affinity for the surfaces of clay minerals, while cadmium is relatively leachable in soil solution.

Therefore, this research aims to assess the potential of bentonite to reduce the risks of heavy metal pollution with promote the sustainable use of contaminated soil, as well as enhancing soil physical and hydrological properties.

## **Material and Methods**

### **Study Area and Soil Sampling**

ISSN 2072-3857

Soil samples were taken from one of the fields belonging to College of Agriculture, University of Al-Qadisiya at a depth 0–30 cm. These samples corresponded to the soil employed in this work. To establish soil properties before applying treatments and commencing the pot experiment, the air-dried soil was crushed with a polyethylene hammer and sieved through a 2-mm sieve for chemical as well as physical analysis.

#### **Experimental Design and Treatments**

The experiment was arranged in Randomized Complete Block Design (RCBD) with three replications. Means were separated using LSD test ( $P < 0.05$ ) through the GenStat software based on statistical analysis of data. The study involved various degrees of lead (Pb) and cadmium (Cd) contamination. Lead treatments comprised of four levels (0, 10, 100 and 200 mg kg<sup>-1</sup>) and cadmium treatments contained four levels (0, 5, 15 and 25 mg kg<sup>-1</sup>). Bentonite was used at two levels (25% and 50%) and a control treatment had no heavy metals or bentonite. The Objective from that to compare the combined and separate effects of heavy metals and bentonite on soil properties, as well as the movement of heavy metals.

#### **Preparation of Soil and Pot Experiment**

Soil was air-dried, ground, and sieved to pass through a 4 mm mesh for pot cultivation (but part of it was passed through a 2 mm mesh for physical-chemical analysis before planting). Plants were grown in plastic pots of 15 kg capacity (30 cm upper diameter, 25 cm base diameter and 33 cm height), filled with 10 kg soil, each.

#### **Soil Pollution and Bentonite Application**

Soil pollution was achieved with lead and cadmium nitrate salts in the experimental levels. Bentonite was applied as a dry powder at specified application rates. The mixture was well homogenized and allowed to settle for two days before planting.

#### **Planting Experiment and Crop Management**

The test plant was the brown Indian Mustard (*Brassica juncea*). Plants were grown from seeds (27/10/2024) and after 30 days, thinned to obtain one plant in each pot. The amount of NPK per pot was 6 g in accordance with recommended fertilization practice. The crop was irrigated with tap water at field capacity and watering began again after attaining 50% of available water.

#### **Soil Physical and Chemical Analyses**

**Soil pH:** Soil pH was measured in a 1:1 soil-to-water suspension using a pH meter according to [9]

**Electrical Conductivity (EC):** Electrical conductivity was determined in a 1:1 soil-to-water suspension using an EC meter following [9]

**Cation Exchange Capacity (CEC):** CEC was determined using the methylene blue method suitable for calcareous and gypsiferous soils according to [10]

**Bulk Density:** Bulk density was measured using the core method according to [11]

**Particle Density:** Particle density was determined using the pycnometer method following [11]

**Total Porosity:** Total porosity was calculated from bulk and particle density values according to the standard relationship described by [12]

**Saturation Percentage:** Saturation percentage was determined as the

percentage of water retained at full saturation according to standard procedures described by [12]

#### **Field Capacity and Permanent Wilting Point:**

Field capacity and permanent wilting point were determined using the soil moisture Characteristic curve described

by [13]

**Hydraulic Conductivity:** Hydraulic conductivity was determined using the standard laboratory method for measuring water movement through saturated soil according to [14]

### **Results and Discussion**

#### **Soil Chemical Properties (pH, EC and CEC)**

The findings indicated that there were statistically significant differences at the probability level ( $P \leq 0.05$ ) in soil chemical characteristics resulting from the introduction of lead (Pb) and cadmium (Cd) with bentonite. Treatment C0 showed the highest pH value (8.08), indicating an alkaline nature of the soil before heavy metal contamination and clay amendment. All treatments and addition of lead nitrate alone and chemical form cadmium nitrate with bentonit statistically reduced pH compared to controls but the values were still within alkaline range. (several interacting effects). Cadmium nitrate ( $\text{Cd}(\text{NO}_3)_2$ ) and lead nitrate ( $\text{Pb}(\text{NO}_3)_2$ ) cause the release of  $\text{Cd}^{2+}$  and  $\text{Pb}^{2+}$  ions in the soil solution. These cations take part in exchange reactions with the adsorbed  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  on clay and carbonate surfaces, which brings about the release of  $\text{H}^+$  ions into the soil solution that caused to decreased pH. Not all target substance will undergo chemical reaction with soil during the extraction, as most Pb and Cd salts in the leachate are hydroxides or basic carbonates which are chemically unstable due to their hydrolysis when present in solution, and cation exchange may be an

additional reason for it [15] [16]. The findings showed that the decrease in pH induced by Pb was more significant than that provoked by Cd. This is probably due to the chemical properties of Pb (especially its higher ionic radius and stronger adsorption affinity for clay minerals, iron oxides than Cd)[17]; [18]. However, there was little change in the overall pH reduction. [19] reported that alkaline soils were of high buffering capacity and hence there was limited propensity for large changes in soil reaction. The decrease in pH from lithification to post-dewatering conditions was also due, in part, to the addition of bentonite. Bentonite is a 2:1 expanding clay mineral with permanent negative charges and high specific surface area that promote surface reactions and cation exchange. Some types of bentonite may also contain mineral impurities or exchange sites partly saturated with replaceable cations, that could affect ionic balance in the soil solution leading to a minor pH decrease. This is also in line with the results of [20] and [21] who mentioned that bentonite or clays like can alter soil reaction, in particular when materials are combined with sources of mineral contamination. For electrical conductivity (EC), the treatments were significantly different. The least EC value ( $3.51 \text{ dS m}^{-1}$ ) due to untreated soil, expressed the lower soluble salts content for control treatment. The amendment of lead and cadmium nitrates into bentonite raised EC values in all treatments, Especially bentonite with lead at a concentration of 50% bentonite addition.

This enhanced level could be as a result of higher concentration of soluble ions in the soil solution following the dissociation of Pb and Cd nitrate salts to  $\text{Pb}^{2+}$ ,  $\text{Cd}^{2+}$ ,  $\text{NO}_3^-$  ions leading to an increase in ionic strength and EC [15] [16] Furthermore, some inhibitors might have temporarily increased EC in a manner similar to the

release of exchangeable cations such as  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$  and  $\text{Na}^+$  through soil wetting with bentonite micronization treatment resulting in increase of total soluble salt. [22] and [20] observed that moderate rise of EC after the amendment of clay is often encountered and it may not be a detrimental process if values are

maintained within thresholds for non-saline stress. All EC values obtained in the current communication were within the moderate salinity ( $<4 \text{ dS}^{-1}$ ) category suggesting that application of bentonite had not caused deleterious salinity but brought about enhancement in other soil properties.

**Table 1. Some Chemical Properties of Soil as Affected by Lead, Cadmium, and Bentonite Treatments.**

Cation Exchange Capacity (CEC) $\text{Cmol}(+) \text{kg}^{-1}$	Electrical Conductivity (EC) $\text{dS m}^{-1}$	pH	Treatments	Cation Exchange Capacity (CEC) $\text{Cmol}(+) \text{kg}^{-1}$	Electrical Conductivity (EC) $\text{dS m}^{-1}$	pH	Treatments
11.73	3.51	8.08	0cd + 0 Bentonite = X0 (Control)	11.73	3.51	8.08	0Pb + 0 Bentonite = X0
15.90	3.68	7.81	5cd+ 25 Bentonite = X1	18.27	3.72	7.73	10Pb + 25 Bentonite = X1
23.67	4.06	7.75	5cd+ 50 Bentonite = X2	25.27	3.89	7.65	10Pb + 50 Bentonite = X2
17.37	3.83	7.84	15cd+ 25 Bentonite = X3	17.93	3.69	7.72	100Pb + 25 Bentonite = X3
24.43	4.06	7.80	15cd+ 50 Bentonite = X4	24.87	4.13	7.61	100Pb + 50 Bentonite = X4
16.67	3.76	7.92	25cd+ 25 Bentonite = X5	17.53	3.78	7.63	200Pb + 25 Bentonite = X5
22.77	3.95	7.87	25cd+ 50 Bentonite = X6	24.40	4.16	7.58	200Pb + 50 Bentonite = X6
0.1391	0.0278	0.0319	L.S.D 0.05	0.2590	0.0361	0.0403	L.S.D 0.05
	1	3			7	7	

The values of cation exchange capacity (CEC) are indicated in Table (1). This had a considerable increase in the case of bentonite application. The lowest CEC value,  $11.73 \text{ cmol}(+) \text{ kg}^{-1}$  was recorded in the control, while there were appreciable increase of these with the treatments containing bentonite. The highest values

were obtained for X4 ( $24.43 \text{ cmol}(+) \text{ kg}^{-1}$ ) treated with cadmium and group X2 ( $25.27 \text{ cmol}(+) \text{ kg}^{-1}$ ) with lead. Overall, the results in the table 1 show that the treatments of bentonite with lead have shown significant differences, unlike the treatments of bentonite with cadmium.

The increased CEC values were manifested directly in soil by the behavior

of Pb and Cd. Lead was more immobilized than cadmium because of its strong adsorption affinity and the occurrence of more stable complexes, whereas cadmium still stayed mobile relatively in solution but with less availability after addition of bentonite [23]

### **Soil Physical Properties (Bulk Density, Total Porosity, and Particle Density)**

Data in Table 2 show that soil physical properties exhibited a slightly significant difference between treatments at the probability level of ( $P \leq 0.05$ ) as a result of adding lead (Pb), cadmium (Cd) in conjunction with bentonite. The highest bulk density value ( $1.57 \mu\text{g m}^{-3}$ ) was observed in the control treatment C0, which probably cultivates soil with no amendment to ameliorate its structure. This resulted in the elevation of particle consolidation and a decrease in the total porosity, which destabilized the soil aeration and water flowing through of root movement. However, there were consistent reduction in bulk density among all treatments when bentonite was applied compared with control. The decrease was greater in the higher application rate and the treatment (X2 Pb 200) contaminated with lead, cadmium showed lower bulk density ( $1.39$  and  $1.40 \text{ g cm}^{-3}$ ), respectively. This decrease may be due to the physical properties of bentonite as a fine-grained clay with low bulk density

and high specific surface area. It increases aggregation of finer particles and contributes to a more stable soil structure, reducing compaction and increasing porosity [24]; [25]

These results were also reflected in the effect of different contents Pb and Cd on soil bulk density, which did not play a direct role when bentonite were equal to each other, it can be implied that it is unlikely for heavy metals to change soil structure. Nevertheless, the incidence of  $\text{Pb}^{2+}$  and  $\text{Cd}^{2+}$  might indirectly affect stability structural due to their interaction with clay mineral and FeO surfaces although not as much as that by [17]; [18]. The decrease in bulk density was immediately translated to an increase in total porosity. The lowest porosity (39.67%) was found in the control treatment, while bentonite-amended treatments presented higher values, exceeding 43.23% and 43.10% respectively in treatment (X2) polluted by cadmium and lead. This increase could also emphasize the efficient keystone of bentonite in enhancing soil structure by creating micro and macropores that results to more total pore volume and good distribution of pores. Recent evidences demonstrated that application of expanding clay minerals such as bentonite improved the total porosity and reduced compaction even in heavy metal contaminated soils [26]; [27].

**Table 2. Some Physical Properties of Soil as Affected by Lead, Cadmium, and Bentonite Treatments.**

Total Soil Porosity (%)	Particle Density $\mu\text{g m}^{-3}$	Bulk Density $\mu\text{g m}^{-3}$	Treatments	Total Soil Porosity (%)	Particle Density $\mu\text{g m}^{-3}$	Bulk Density $\mu\text{g m}^{-3}$	Treatments
39.67	2.61	1.57	0cd + 0 Bentonite = X0 (Control)	39.67	2.61	1.57	0Pb + 0 Bentonite = X0
41.23	2.53	1.49	5cd+ 25 Bentonite = X1	40.37	2.53	1.51	10Pb + 25 Bentonite = X1
43.23	2.46	1.40	5cd+ 50 Bentonite = X2	43.10	2.44	1.39	10Pb + 50 Bentonite = X2
40.57	2.56	1.52	15cd+ 25 Bentonite = X3	40.63	2.51	1.49	100Pb + 25 Bentonite = X3
42.13	2.44	1.42	15cd+ 50 Bentonite = X4	42.27	2.46	1.42	100Pb + 50 Bentonite = X4
40.37	2.51	1.50	25cd+ 25 Bentonite = X5	40.50	2.54	1.51	200Pb + 25 Bentonite = X5
42.43	2.45	1.41	25cd+ 50 Bentonite = X6	42.93	2.45	1.40	200Pb + 50 Bentonite = X6
0.8078	0.00964	0.02103	L.S.D 0.05	0.5883	0.01487	0.01758	L.S.D 0.05

The data of soil particle density were significantly different at this level. The control treatment registered the highest particle bulk density ( $2.61 \mu\text{g m}^{-3}$ ), indicating the presence of primary minerals with high density like quartz and feldspar in the untreated soil. Particle density in all the treatments between with the application of bentonite ( $2.44$  to  $2.56 \mu\text{g m}^{-3}$ ). The minimum values were recorded from cadmium and lead contaminated treatments (X4 and X2, respectively) whereas the maximum particle dense condition was observed in cadmium treated one (X3).

This decrease could be explained by the high content of smectite minerals in bentonite and that the particle density is lower than that of primary minerals contained in the soils. As a result, the overall average particle density is reduced with inclusion of bentonite in the soil. With increasing bentonite content modified apparent mineral composition can be obtained and the soil particles arrangement can also be changed to an extent, which is beneficial to improving general soil physical properties [26]; [28]

In conclusion, these findings suggest that bentonite and Pb and Cd had acted as a key contributor to alteration in soil physical, chemical and surface interaction without significantly affect the structural

modification. The improvement in the physical properties by the application of bentonite was also responsible for the decrease in mobility of Pb<sup>2+</sup> and Cd<sup>2+</sup> in soil as microporosity increases, allowing to improve soil structure, favoring not only retention power on these metals, but also preventing them from being absorbed by plants.

**Soil Hydrological Properties**

According to the Table (3), there were significant differences at probability level (P ≤ 0.05) between hydrological properties of soil contaminated with lead and cadmium as affected by bentonite addition. The LSD (0.05) for saturation percentage was 0.1700 and for Cd, respectively, at 0.2704 for Pb; it was 0.2114 and 0.2202 for field capacity; it was 0.1639 and 0.1662 for permanent wilting point, and finally Hydraulic conductivity was 0.1027 and this value is considered more accurate than other methods due to high flexibility in estimation of small uncertainties of the model-generated data like hydraulic conductivity.

The lowest saturation percentage value of 37.87% of the control (X0) was observed

in both introductive treatments, indicating that untreated soil had poor water holding capacity due to low porosity and lack of expanding clay minerals (Hillel, 2004[12]; Brady&Weil, 2017). [29] All the addition of bentonite dramatically enhanced saturation percentage, which could reach 45.53% in Cd treatment (X2), and it was used to be up to 46.03% in X6, meanwhile for Pb treatments, it reached 45.63 % ( X2) and higher 46.27%(X4). This increase is explained through the large water adsorption/retention capacity occurring in bentonite interlayer spaces as well as an increasing relative proportion of micropores holding water at saturation [30]; [31]

Bentonite application also led to a significantly higher field capacity for both metals. Under Cd treatment, it increased from 15.57% (in the control) to 20.80–20.83%, while under Pb treatment it attained 21.27–21.53%. This improvement is the result of greater capacity of soil for holding plant available water after drainage gravity, because of the fenestration improvement caused by the incorporation of bentonite fine and middle pores [32].[33]

**Table 3. Some Hydrological Properties of Soil as Affected by Lead, Cadmium, and Bentonite Treatments.**

Treatment	Saturation Capacity	Field Capacity (FC)	Permanent Wilting Point (PWP) %	Hydraulic Conductivity	Treatments	Saturation Capacity	Field Capacity (FC)	Permanent Wilting Point (PWP) %	Hydraulic Conductivity
OPb + 0 Bentonite = X0	37.87	15.57	6.43	4.73	Ocd + 0 Bentonite = X0	37.87	15.57	6.43	4.73

					(Control)					
10Pb + 25	42.1	18.7	8.47	3.77	5cd+ 25	42.00	18.4	8.20	4.07	
Bentonite	3	0			Bentonite		7			
= X1					= X1					
10Pb + 50	45.6	21.2	9.83	2.93	5cd+ 50	45.53	20.8	9.37	3.17	
Bentonite	3	7			Bentonite		0			
= X2					= X2					
100Pb + 25	41.9	18.8	8.27	3.93	15cd+ 25	41.80	18.1	8.47	3.97	
Bentonite	7	3			Bentonite		7			
= X3					= X3					
100Pb + 50	46.2	21.5	9.50	3.03	15cd+ 50	45.20	20.8	9.77	3.00	
Bentonite	7	3			Bentonite		3			
= X4					= X4					
200Pb + 25	41.8	18.6	7.83	3.90	25cd+ 25	41.57	18.0	7.77	4.10	
Bentonite	3	0			Bentonite		0			
= X5					= X5					
200Pb + 50	45.4	21.2	9.83	3.07	25cd+ 50	46.03	20.6	10.20	3.10	
Bentonite	7	3			Bentonite		3			
= X6					= X6					
L.S.D 0.05	0.27	0.22	0.1662	0.115	L.S.D 0.05	0.170	0.21	0.1639	0.102	
	04	02		4		0	14		7	

Indeed, followed by an increase in the PWP of 6.43% detected between CT and treatments where NPK were placed at the top or inside the columns; significant increase in water stress also occurred to reach up to 10.20% for Cd contaminant (X2) and 9.83% for Pb one (X2,X6) at highest rate application of bentonite. Such increase could be due to the higher volume of micropores which are persistent under high matric forces as well as the expansive nature of bentonite and high water holding capacity within its lamellar structure [34].

Hydraulic conductivity ( $K_s$ ) values are also reported in Table (3). The value of  $K_s$  was highest in the control (4.73), while bentonite application significantly decreased  $K_s$  to 3.00 under Cd treatments and ranged from 2.93 to 3.93 in Pb treatments, respectively. This decline is due to the swelling of bentonite-plates, obstructing or compressing large pores

conducting water rapidly and reducing deep percolation losses and enhancing water retention efficiency in the root zone [35]; [36]

It was found that bentonite was the main factor for changing soil hydrological properties. By contrast] its changes of Pb or Cd content had little effect directly when the content of bentonite was constant, which explained the role of clay amendment in alleviating sensitivity of heavy metal contamination to soil system.

### Conclusions and Recommendations

The findings showed that the addition of bentonite was efficient in immobilizing soil-born lead (Pb) and cadmium (Cd), which reduced their leachability, short-term extractability, and bioavailability in the decreasing order of Pb>Cd. The main effects of bentonite are physical and hydrological, decreasing bulk density, increasing total porosity and water retention capacity, and reducing hydraulic

conductivity; in turn the principal effects of Pb and Cd are chemical (minimal decrease in pH) with increases below regulation permitted standards. According to the results, bentonite can be recommended as an efficient and environmentally friendly amendment for soils contaminated with Pb and Cd. Higher application rates are suggested, especially for severely contaminated soils, to improve the structure and water holding ability of soil with low risk of HMs. Application of bentonite treatment in sustainable soil management programs is recommended, as well future long-term studies to test the stability of Pb and Cd immobilization and the interaction with crops and fertilizers to ensure its field applicability.

## References

- [1] **Ali, H., Khan, E., & Ilahi, I. 2019.** Environmental chemistry and ecotoxicology of hazardous heavy metals. *Chemosphere*, 228, 429–448.
- [2] **Shahid, M., et al. 2020.** Cadmium bioavailability and accumulation in plants: A review. *Environmental Pollution*, 261, 114–122
- [3] **Bradl, H. B. 2004.** Adsorption of heavy metal ions on soils and soils constituents *Journal of Colloid and Interface Science*, 277(1), 1–18.
- [4] **Tóth, G., Hermann, T., & Da Silva, M. R. 2024.** Heavy metals in agricultural soils: Sources, impacts and mitigation strategies. *Environmental Research*, 238, 117102.
- [5] **Li, Z., Wu, S., & Wang, J. 2024.** Interactions between soil physical properties and heavy metal mobility. *Journal of Environmental Sciences*, 137, 120–132.
- [6] **Sun, Y., Li, Y., Xu, Y., Liang, X., & Wang, L. 2023.** Bentonite-based amendments for immobilization of heavy metals and soil quality improvement. *Chemosphere*, 332, 138819.
- [7] **Hernández-Soriano, M. C., Peña, A., & Cox, L. 2024.** Clay minerals as regulators of soil physical structure and contaminant dynamics. *Soil & Tillage Research*, 239, 105942.
- [8] **Gao, P., Zhang, Y., & Liu, H. 2024.** Influence of soil amendments on hydraulic behavior and metal transport in soils. *Journal of Hydrology*, 628, 129273.
- [9] **Wei, X., Chen, L., & Zhou, Q. 2025.** Sustainable management of metal-contaminated soils using clay minerals. *Soil Systems*, 9(1), 21.
- [10] **age, E. R. ; R. H. Miller and D. R. Kenny . 1982.** Methods of soil analysis , Part 2 , 2nd ed. Agron. 9 .
- [11] **Savant, N. K .1994.** Simplified methylene blue method rapid determination of cation exchange capacity of mineral soils. *Commun. Soil Sci. Plant. Anal* , 25 (19 & 20): 3357-3364,
- [12] **Blake, G., & Hartge, K. H. 1986.** Bulk density. *Methods of soil analysis: Part 1 Physical and mineralogical methods*, 5, 363-375.
- [13] **Hillel, D. 2004.** Introduction to Environmental Soil Physics. Elsevier.
- [14] **Richards, L.A. 1954.** Diagnosis and improvement of saline and alkali soils. U.S. Dept. of Agri. Handbook No.60: 69-82.
- [15] **Klute, A., & Dirksen, C. 1986.** Hydraulic conductivity and diffusivity: Laboratory methods. *Methods of soil analysis: Part 1 physical and mineralogical methods*, 5, 687-734.
- [16] **Shaheen, S. M., et al. 2022.** Soil pH buffering and heavy metal behavior under clay amendments. *Journal of Hazardous Materials*, 424, 127–136.
- [17] **Park, J. H., et al. 2023.** Heavy metal salts and soil chemical behavior.

- Journal of Hazardous Materials, 452, 131180.
- [18] **McBride, M. B.**1994.Environmental chemistry of soils.New York, USA: Oxford University Press
- [19] **Kabata-Pendias, A.**2011 .Trace elements in soils and plants (4th ed.).Boca Raton, FL, USA: CRC Press, Taylor&Francis Group.
- [20] **Alloway, B. J.** 2013. Heavy Metals in Soils: Trace Metals and Metalloids in Soils and their Bioavailability (3rd ed.). Springer.
- [21] **Zhang, Y., et al.** 2022. Clay minerals influence soil chemical properties and metal availability. *Geoderma*, 409, 115–123.
- [22] **Nie, X., et al.** 2024. Effect of bentonite amendment on soil water retention characteristics and pore size distribution. *Geoderma*, 435, 116–125.
- [23] **Radziemska, M., et al.** 2018. Effect of clay amendments on soil salinity and heavy metal behavior. *Applied Clay Science*, 161, 206–213.
- [24] **Wang, L., et al.** 2024. Clay mineral amendments improve cation exchange capacity and reduce cadmium bioavailability in contaminated soils. *Soil & Tillage Research*, 236, 105–118.
- [25] **Ahmed, S. A., Mahmoud, E. K., & El-Kader, N. A.** 2024. Role of bentonite in improving soil physical quality and mitigating cadmium-induced compaction. *Environmental Science and Pollution Research*, 31, 21487–21501.
- [26] **Wang, J., Zhang, L., Zhou, Y.,&Sun, Q.**2025. Soil bulk density and porosity responses to bentonite amendment in metal-contaminated soils. *Journal of Soils and Sediments*, 25, 1189–1201.
- [27] **Zhang, Y., Liu, X., Chen, H., & Wang, J.** 2023. Soil porosity and its relationship with soil structure and amendments. *Geoderma*, 424, 115–123.
- [28] **El-Naggar, A., Shaheen, S. M., Ok, Y. S., & Rinklebe, J.** 2024. Clay-based amendments reduce cadmium mobility and bioavailability in polluted soils. *Science of the Total Environment*, 906, 167541.
- [29] **Kim, S. J.,&Park, J. H.** 2025. Particle density response of contaminated soils to clay-based amendments. *Soil Systems*, 9(1), 18
- [30] **Brady, N. C.,&Weil, R. R.** 2017. *The Nature and Properties of Soils*. Pearson.
- [31] **Rashid, M., et al.** 2023. Water retention improvement using bentonite. *Environmental Pollution*, 318, 120874.
- [32] **Chen, Y.,&Wu, L.** 2025. Enhancement of soil saturation capacity and pore-water storage using clay mineral amendments. *Journal of Hydrology*, 634, 130515.
- [33] **Singh, B. K., Delgado-Baquerizo, M., Egidi, E., Guirado, E., Leach, J. E., Liu, H., & Trivedi, P.** 2023. Climate change impacts on plant pathogens, food security and paths forward. *Nature Reviews Microbiology*, 21(10), 640-656.
- [34] **López-Garrido, B., Gil-Pita, R., Cortázar-Neira, Í., Rogers, A.,&Ojeda-Gallego, C.** 2024, August). Improving Fetal Heart Sounds Using Deep Learning and Smart Signal Processing. In 2024 IEEE International Conference on Technology, Informatics, Management, Engineering and Environment (TIME-E) (Vol. 5, pp. 93-99). IEEE.
- [35] **Abdelrahman, H.,&Hassan, A.** 2024. Soil water retention characteristics as affected by clay amendments under metal stress. *Soil&Tillage Research*, 236, 105856.
- [36] **Salazar-Cruz, B., López-Vázquez, E., &Hernández-Moreno, J. M.**

**2024.** Effect of bentonite amendment on water flow and pore-size distribution in agricultural soils. Soil&Tillage Research, 241, 105896.

[37] **Nguyen, T. H., Tran, D. Q.,&Vo, P. L. 2025.** Reduction of hydraulic conductivity and contaminant mobility in clay-amended soils. Journal of Hydrology, 631, 130298.