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Mitigation of cadmium, lead and copper uptake in French beans (Phaseolus vulgaris L.) using Vermicompost-assisted phytomanagement under contaminated irrigated soils

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Abstract

French bean (*Phaseolus vulgaris* L.) is a high-value vegetable crop widely grown under irrigated conditions; however, its production in contaminated soils raises concerns due to the accumulation of heavy metals in edible tissues. Continuous use of polluted irrigation water introduces cadmium (Cd), lead (Pb), and copper (Cu) into the soil–plant system, posing potential risks to human health through the food chain. This study evaluated the combined effects of irrigation methods and soil amendments on the uptake of Cd, Pb, and Cu in French bean grown under contaminated irrigated conditions in Kabaa Irrigation Scheme, Machakos County, Kenya. Field experiments were conducted during two consecutive cropping seasons (short rains 2021 and long rains 2022) using a split-plot arrangement in a randomized complete block design with three replications. Irrigation methods (basin and furrow) were assigned to main plots, while soil amendments (control, fertium, farmyard manure, gypsum + farmyard manure, and vermicompost) were applied to subplots. Heavy metal uptake in roots, shoots, and pods was determined based on biomass and tissue metal concentrations. Results showed that heavy metal accumulation varied significantly ($p \leq 0.05$) across treatments, with roots consistently recording higher uptake than shoots and pods. Vermicompost markedly reduced Cd, Pb, and Cu uptake across plant tissues, with the lowest values observed in pod tissues (Pb: 0.003 kg ha^{-1}; Cd: 0.005 kg ha^{-1}; Cu: 0.01 kg ha^{-1}). Similarly, furrow irrigation consistently resulted in lower metal uptake compared to basin irrigation across both seasons. The combined application of vermicompost and furrow irrigation produced the greatest reduction in heavy metal accumulation. These reductions were associated with enhanced immobilization, adsorption, and complexation of metals within the soil matrix, alongside improved regulation of moisture dynamics in the root zone. From a remediation perspective, the findings demonstrate that integrating vermicompost with appropriate irrigation management can significantly limit metal mobility and transfer into edible plant parts. Therefore, this approach represents a practical and sustainable phytomanagement strategy for mitigating heavy metal risks in contaminated irrigated agroecosystems while supporting safer crop production.

NOVELTY STATEMENT

This study presents a novel field-based phytomanagement strategy that integrates vermicompost application with irrigation method optimization to mitigate cadmium, lead, and copper uptake in French bean under contaminated irrigation systems. The findings provide new evidence that irrigation regime is not merely a water management tool but a critical regulator of heavy metal bioavailability and plant uptake when combined with organic amendments. By demonstrating that vermicompost and furrow irrigation act synergistically to enhance metal immobilization and reduce transfer to edible tissues, this study advances current understanding of integrated remediation strategies and offers a practical solution for safer crop production in contaminated agroecosystems.

1. Introduction

The increasing contamination of agricultural soils with heavy metals has emerged as a major environmental and food safety concern, particularly in irrigated agroecosystems where the use of wastewater and effluent-derived irrigation sources is common (Escalante-Mañe et al.2026). Cadmium (Cd), lead (Pb), and copper

(Cu) are among the most prevalent contaminants due to their persistence, non-biodegradability, and potential to accumulate in soils and crops over time. Their entry into the food chain through plant uptake poses significant risks to human health, including toxicity, bioaccumulation, and long-term ecological disruption (Angon et al. 2024; Gupta et al. 2024).

The behavior of heavy metals in the soil–plant system is governed by complex interactions involving soil physicochemical properties, moisture dynamics, and plant physiological processes (Gavrilescu 2021). Plants primarily absorb metals through their roots, followed by partial translocation to aerial tissues via the transpiration stream. While essential elements such as Cu play key roles in plant metabolic processes, excessive accumulation—similar to non-essential metals such as Cd and Pb—can disrupt enzymatic activities, impair photosynthesis, and induce oxidative stress (Mitra et al. 2020; Raza et al. 2024). In most cases, plant roots act as a partial barrier to metal movement, resulting in higher accumulation in roots relative to shoots and edible tissues, although this balance is strongly influenced by environmental conditions and management practices (Karić et al. 2021).

Irrigation practices are a critical yet often underexplored factor influencing heavy metal bioavailability and uptake. Water application methods directly affect soil moisture distribution, redox conditions, and solubility of metal ions in the rhizosphere (Sui et al. 2026). Basin irrigation, characterized by prolonged water retention and localized saturation, can enhance metal dissolution and increase their availability for plant uptake. In contrast, furrow irrigation promotes better soil aeration and controlled water flow, potentially limiting metal mobility and uptake (Demissie et al. 2022; Ahmad et al. 2021). Despite these contrasting effects, the role of irrigation method in regulating heavy metal uptake under field conditions remains insufficiently documented, particularly in smallholder vegetable production systems.

Soil amendments have been widely investigated as a practical approach to mitigate heavy metal bioavailability in contaminated soils (Nunes et al. 2021). Organic amendments such as farmyard manure and vermicompost are rich in humic substances and functional groups capable of binding metal ions through adsorption, complexation, and ion exchange processes. These mechanisms reduce the mobility and phytoavailability of metals, thereby limiting their uptake by crops (Kim et al. 2022; Paradelo et al. 2023). Vermicompost, in particular, has received growing attention due to its high microbial activity and enhanced capacity to stabilize heavy metals in soil matrices, making it a promising tool for sustainable soil remediation and crop production (Sarfraz et al. 2024).

Although the individual effects of irrigation practices and soil amendments on heavy metal dynamics have been widely studied, there remains limited field-based evidence on their combined influence on metal uptake and partitioning in vegetable crops grown under contaminated irrigation systems (Sumudumali and Abeywickrema 2026). French bean (*Phaseolus vulgaris* L.), a high-value horticultural crop widely cultivated under irrigation, is particularly susceptible to heavy metal accumulation due to its rapid growth and high nutrient uptake capacity (Nowwar et al. 2022). Understanding how integrated management practices can minimize metal accumulation in edible tissues is therefore essential for ensuring both productivity and food safety.

Therefore, this study aimed to evaluate the combined effects of irrigation methods and soil amendments on cadmium, lead, and copper uptake in different plant tissues (roots, shoots, and pods) of French bean grown under contaminated irrigated soils. The findings provide insights into practical phytomanagement strategies that can be used to reduce heavy metal accumulation in vegetable production systems while maintaining agronomic productivity.

2. Materials and methods

2.1 Study area description

The study was conducted in Machakos County's Kabaa Irrigation Scheme, Kenya. The experiment existed within two successive seasons of short rains (October-December,2021) and long rains (March-May,2022). The experimental site was located between 37.461776 longitude and − 1.247922 latitude. Machakos county usually has an average yearly temperature of 21.1°C and rainfall of 830mm per annum. The site's soils were deep, heavy clay to silty loam, well-drained, and located in the range of 1000m-2100m above sea level.

2.2 Experimental design and field layout

The experiment was laid out using a randomized complete block design with a split plot arrangement and three replications. Irrigation methods, which included basin irrigation and furrow irrigation, were assigned to the main plots. Soil amendments, namely control, fertium (5L/ha^{-1}), farmyard manure (10 tha^{-1}), vermicompost (5 tha^{-1}), gypsum (2 tha^{-1}), and a mixture of gypsum (2 tha^{-1}) and farmyard manure (10 tha^{-1}), were allocated to the subplots. The experimental field was divided into 30 plots, each measuring 3 m by 3 m. A spacing of 1 m was maintained between blocks and 0.5 m between subplots to reduce interference between treatments. Land preparation was carried out before the onset of rains through tractor ploughing, followed by harrowing to obtain a suitable seedbed and improve soil structure and water infiltration. French bean seeds of the Samantha variety were used. Planting was done at a spacing of 30 cm between rows and 15 cm within rows, with one seed placed per hole at a depth of about 2 to 5 cm. All plots were managed uniformly throughout the growing period. Routine agronomic practices such as weeding, pest control, and disease management were carried out consistently across all treatments.

2.3 Sampling and samples preparation

Soil samples were collected from each subplot using a soil auger at a depth of 0 to 10 cm following a random traverse approach. These soil samples were placed in clean sampling bags, air dried, ground, and composited prior to analysis of cadmium, lead, and copper using standard procedures as outlined by Association of Official Analytical Chemists (AOAC) (Rashid et al. 2016).

Irrigation water samples were collected during morning hours to avoid diurnal differences in the quality of water. Acid-washed clean polythene bottles were used in the collection of water samples from the polluted river Athi canal. Three samples taken at each location at 20cm below surface of water to avoid contaminants on surface. These samples were mixed to form a composite sample. The water samples were filtered using Whatman No.42 filter paper to remove particles, digested using concentrated nitric acid

(HNO_3), and stored at 4°C before analysis of cadmium, lead, and copper with an atomic absorption spectrophotometer using the standard procedures as outlined by Association of Official Analytical Chemists (AOAC) (Kassim et al. 2022).

Plant samples were collected at harvest through destructive sampling of tagged plants. The plants were separated into roots, shoots, and pods, washed with deionized water to remove soil particles, and transported to the laboratory. The samples were oven dried at 60°C until a constant weight was reached, then ground into fine powder and stored in labelled containers prior to determination of metal concentrations using standard procedures as outlined by Association of Official Analytical Chemists (AOAC) (Zheljazkov and McNeil 2008).

2.4 Determination of cadmium, lead and copper uptake

Uptake of cadmium, lead, and copper by French bean was determined based on dry matter yield and corresponding metal concentrations in plant tissues using standard procedures as outlined by Association of Official Analytical Chemists (AOAC). The calculation was performed separately for roots, shoots, and pods.

Heavy metal uptake was expressed in kg ha^{-1} and calculated using the following relationship:

$$\text{Uptake} = \frac{(\text{Biomass} \times \text{Concentration})}{100} \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{Equation 1}$$

Biomass represents the dry weight of plant tissues expressed in kg ha^{-1}, and concentration represents the metal content in the respective tissues expressed in mg kg^{-1}. All uptake values were calculated on a dry weight basis.

2.5 Data analysis

Data on heavy metal concentrations were analyzed using analysis of variance in R software version 4.4. Prior to analysis, data were checked for normality and homogeneity of variance using the Shapiro–Wilk and Levene's tests, respectively. Where necessary, appropriate transformations were applied to meet the assumptions of analysis of variance. Treatment means were compared using the Honestly Significant Difference test at a 5% level of significance where significant effects were detected.

3. Results

3.1 Baseline Chemical Characteristics

The baseline chemical properties of the soil and irrigation water indicate that the experimental site was moderately to highly affected by heavy metal contamination and salinity-related constraints (Table 1). Soil concentrations of lead (87.5 mg kg^{-1}), copper (38.4 mg kg^{-1}), and cadmium (1.2 mg kg^{-1}) suggest an elevated presence of potentially toxic elements, which may pose risks to crop safety and human health if

transferred into edible plant tissues. Similarly, the irrigation water contained measurable levels of these metals, particularly lead (5.5 mg L^{-1}) and copper (3.5 mg L^{-1}), indicating a continuous external source of contamination to the soil–plant system.

Table 1
The chemical characteristics of soil found at the experimental site.

Parameter	Value
Copper	38.4 mg/kg
Lead	87.5 mg/kg
Cadmium	1.2 mg/kg
Copper (Irrigating water)	3.5 mg/l
Lead (Irrigating water)	5.5 mg/l
Cadmium (Irrigating water)	0.05 mg/l
p^H	8.1
Cation Exchange Capacity (CEC)	39.0 cmol/kg
Electrical conductivity	4.35 ds/m
Total Nitrogen	0.05(%)
Available Potassium	0.05(%)
Available Phosphorus	0.01%
Total Organic Carbon	0.2%
Exchangeable Sodium Percentage (ESP)	15.1
Sodium Adsorption Ration (SAR)	13.2

The soil p^H of 8.1 reflects slightly alkaline conditions, which can influence metal solubility and availability depending on the specific element. While alkaline p^H may reduce the mobility of some metals, the combined effects of salinity and sodicity observed in this study could counteract this limitation. The relatively high electrical conductivity (4.35 dS m^{-1}), sodium adsorption ratio (13.2), and exchangeable sodium percentage (15.1) indicate saline-sodic conditions, which are known to deteriorate soil structure, reduce permeability, and potentially enhance the mobility of certain metal ions.

The cation exchange capacity of 39.0 cmol kg^{-1} suggests a moderate to high capacity of the soil to retain cations, including heavy metals. However, this potential is limited by the low levels of total organic carbon (0.2%), total nitrogen (0.05%), and available phosphorus (0.01%), which reflect poor soil fertility and reduced buffering capacity against metal toxicity. Low organic matter content in particular reduces the soil's ability to immobilize heavy metals through complexation processes.

The combined characteristics of elevated heavy metal concentrations, saline-sodic conditions, and low organic matter indicate a degraded soil environment with a high likelihood of metal bioavailability and plant uptake. These conditions justify the need for appropriate soil amendments and improved irrigation practices to reduce metal mobility and accumulation in crop tissues.

3.2 Effects of irrigation method and soil amendments on lead uptake in French bean tissues

Lead uptake in French bean tissues varied significantly among soil amendments and irrigation methods across both cropping seasons (Table 2). In all treatments, lead accumulation consistently followed the order root > shoot > pod, indicating that the highest concentrations were retained in the root tissues while the least amounts were observed in the pods.

Table 2
Effects of methods of irrigation and soil amendments on uptake of lead metal (kg ha⁻¹) in roots, shoots and pods

Factor		2021 Short rains			2022 Long rains		
	Treatments	**RUPT**	**SUPT**	**PUPT**	**RUPT**	**SUPT**	**PUPT**
Soil Amendments	Control	0.0624^{a}	0.0471^{a}	0.0288^{a}	0.1477^{a}	0.0765^{a}	0.0415^{a}
	Fertium	0.0369^{b}	0.0225^{b}	0.024^{ab}	0.0766^{b}	0.0528^{b}	0.026^{b}
	Farmyard	0.0234^{c}	0.0102^{c}	0.0071^{bc}	0.0476^{c}	0.0275^{c}	0.0105^{c}
	Gypsum+farmyard	0.0101^{d}	0.0061^{d}	0.0042^{c}	0.0257^{d}	0.0085^{d}	0.0056^{d}
	Vermicompost	0.0061^{e}	0.0041^{e}	0.0025^{c}	0.0091^{e}	0.0022^{e}	0.0038^{e}
p-value		< 0.001	< 0.001	< 0.05	< 0.001	< 0.001	< 0.001
Irrigation	Basin	0.0183^{a}	0.0040^{a}	0.0151^{a}	0.0818^{a}	0.0404^{a}	0.0210^{a}
	Furrow	0.0061^{b}	0.0120^{b}	0.0100^{a}	0.0409^{b}	0.0266^{b}	0.0131^{b}
p-value		< 0.001	< 0.001	ns	< 0.001	< 0.001	< 0.001
Means followed by different letter in a column are significantly different at p ≤ 0.05							
PUPT = Pod Uptake; SUPT=Shoot Uptake; SUPT=Root Uptake; Season one (Short rains); season two (Long rains)							

Soil amendments had a marked effect on lead uptake in all plant tissues. The control treatment recorded the highest uptake values in both seasons, with root uptake increasing from 0.0624 kg ha⁻¹ in the short rains to 0.1477 kg ha⁻¹ in the long rains. A clear reduction in lead uptake was observed with the application of amendments. Fertium showed lower uptake compared to the control, followed by farmyard manure and the gypsum plus farmyard manure mixture. Vermicompost consistently recorded the lowest lead uptake

across all tissues and seasons, with root uptake values of 0.0061 kg ha^{-1} in the short rains and 0.0091 kg ha^{-1} in the long rains. Similar trends were observed in shoots and pods, where uptake values decreased progressively from the control to vermicompost treatments.

Irrigation method also significantly influenced lead uptake in most cases. Basin irrigation resulted in higher uptake compared to furrow irrigation across both seasons. In the long rains, basin irrigation recorded root uptake of 0.0818 kg ha^{-1}, while furrow irrigation recorded 0.0409 kg ha^{-1}. A similar pattern was observed in shoots and pods, where basin irrigation consistently showed higher values. In the short rains, irrigation effects were significant for root and shoot uptake, while pod uptake did not differ significantly between irrigation method.

3.3 Effects of interactions between methods of irrigation and soil amendments on uptake of lead metal in roots, shoots and pods

The highest lead uptake was observed under the control combined with basin irrigation in both seasons. In the short rains, this treatment recorded root, shoot, and pod uptake values of 0.0815, 0.0617, and 0.0462 kg ha^{-1}, respectively (Table 3). A similar trend was observed in the long rains, where uptake increased to 0.2021 kg ha^{-1} in roots, 0.0917 kg ha^{-1} in shoots, and 0.0516 kg ha^{-1} in pods. In contrast, the combination of control with furrow irrigation showed lower uptake across all plant tissues.

Table 3
Effects of interactions between methods of irrigation and soil amendments on uptake of lead metal (kg ha^{-1}) in roots, shoots and pods

Treatments	2021 Short rains			2022 Long rains		
	RUPT	SUPT	PUPT	RUPT	SUPT	PUPT
Control Basin	0.0815^{a}	0.0617^{a}	0.0462^{a}	0.2021^{a}	0.0917^{a}	0.0516^{a}
Control Furrow	0.0530^{b}	0.0327^{b}	0.0285^{ab}	0.0933b	0.0632^{b}	0.0324^{b}
Fertium Basin	0.0433^{c}	0.0325^{c}	0.0124^{bc}	0.0911^{c}	0.0613^{c}	0.0315^{c}
Fertium Furrow	0.0316^{d}	0.0133^{d}	0.0113^{bc}	0.0631^{d}	0.0423^{d}	0.0209^{d}
Farmyard Basin	0.0208^{e}	0.0123^{e}	0.0089^{bc}	0.0620^{e}	0.0338^{e}	0.0119^{e}
Farmyard Furrow	0.0152^{f}	0.0071^{f}	0.0060^{c}	0.0402^{f}	0.0211^{f}	0.0091^{f}
Gypsum+Farmyard Basin	0.0122^{g}	0.0061^{f}	0.0052^{c}	0.0321^{g}	0.0100^{g}	0.0081^{g}
Gypsum+Farmyard Furrow	0.0082^{h}	0.0052^{g}	0.0029^{c}	0.0122^{h}	0.0071^{h}	0.0031^{h}
Vermicompost Basin	0.0081^{h}	0.0051^{g}	0.0004^{c}	0.0111^{i}	0.0061^{i}	0.0009^{i}
Vermicompost Furrow	0.0041^{i}	0.0020^{h}	0.0001^{c}	0.0061^{j}	0.0033^{j}	0.0008^{i}
p-value	< 0.001	< 0.001	< 0.05	< 0.001	< 0.001	< 0.001
Means followed by different letter in a column are significantly different at p ≤ 0.05						
PUPT = Pod Uptake; SUPT=Shoot Uptake; SUPT=Root Uptake; Season one (Short rains); season two (Long rains)						

A progressive reduction in lead uptake was observed with the application of soil amendments under both irrigation methods. Fertium and farmyard manure treatments recorded intermediate uptake levels, while the gypsum and farmyard manure combination further reduced lead accumulation. The lowest uptake values were consistently recorded under vermicompost treatments, particularly when combined with furrow irrigation.

Under vermicompost with furrow irrigation, root uptake decreased to 0.0041 kg ha^{-1} in the short rains and 0.0061 kg ha^{-1} in the long rains. Corresponding shoot and pod uptake values were also minimal, with pod uptake reaching as low as 0.0001 kg ha^{-1} in the short rains and 0.0008 kg ha^{-1} in the long rains. Across all soil amendments, basin irrigation consistently resulted in higher lead uptake compared to furrow irrigation within the same treatment category.

3.4 Effects of irrigation method and soil amendments on cadmium uptake in French bean tissues

Soil amendments showed a clear and progressive reduction in cadmium uptake across all plant tissues (Table 4). The control treatment recorded the highest uptake values in both seasons, with root uptake increasing from 1.1102 kg ha⁻¹ in the short rains to 1.6507 kg ha⁻¹ in the long rains. A similar pattern was observed in shoots and pods. The application of fertium resulted in a reduction in uptake compared to the control, followed by further decreases under farmyard manure and the gypsum plus farmyard manure treatment. Vermicompost consistently recorded the lowest cadmium uptake across all plant tissues, with root uptake values of 0.1560 kg ha⁻¹ in the short rains and 0.2006 kg ha⁻¹ in the long rains. Corresponding reductions were also observed in shoots and pods, where the lowest values were recorded under vermicompost treatments.

Table 4
Irrigation and soil amendments influence on uptake of cadmium metal (kg ha⁻¹) in roots, shoots and pods

Factor		2021 Short rains			2022 Long rains		
	Treatments	**RUPT**	**SUPT**	**PUPT**	**RUPT**	**SUPT**	**PUPT**
Soil Amendments	Control	1.1102^{a}	0.8133^{a}	0.0760^{a}	1.6507^{a}	1.2280^{a}	0.6669^{a}
	Fertium	0.7524^{b}	0.5620^{b}	0.0460^{b}	1.1526^{b}	0.7658^{b}	0.2709^{b}
	Farmyard	0.4741^{c}	0.3113^{c}	0.0310^{c}	0.7528^{c}	0.4555^{c}	0.2176^{c}
	Gypsum +farmyard	0.3146^{d}	0.2189^{d}	0.0158^{d}	0.5502^{d}	0.2409^{d}	0.1543^{d}
	Vermicompost	0.1560^{e}	0.0770^{e}	0.0045^{e}	0.2006^{e}	0.0724^{e}	0.0582^{e}
P-value		< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Irrigation	Basin	0.6896^{a}	0.5131^{a}	0.0439^{a}	1.0007^{a}	0.6853^{a}	0.3883^{a}
	Furrow	0.4333^{b}	0.2799^{b}	0.0255^{b}	0.7221^{b}	0.4197^{b}	0.1588^{b}
P-value		< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Means followed by the same letter in a column are not significantly different at p ≤ 0.05							
RUPT=Root Uptake; SUPT=Shoot Uptake; PUPT = Pod Uptake for seasons 1 (Short rain) and season 2 (Long rains)							

Irrigation method also had a significant effect on cadmium uptake. Basin irrigation resulted in higher uptake compared to furrow irrigation across all plant tissues and seasons. In the short rains, basin irrigation recorded root uptake of 0.6896 kg ha⁻¹, while furrow irrigation recorded 0.4333 kg ha⁻¹. This trend was maintained in the long rains, where root uptake under basin irrigation reached 1.0007 kg ha⁻¹ compared to 0.7221 kg ha⁻¹ under furrow irrigation. Similar differences were observed in shoots and pods.

3.5 Interaction effects of irrigation method and soil amendments on cadmium uptake in French bean tissues

The highest cadmium uptake was recorded under the control combined with basin irrigation in both seasons. In the short rains, this treatment resulted in root, shoot, and pod uptake values of 1.3103, 1.0131, and 0.0902 kg ha⁻¹, respectively (Table 5). These values increased further in the long rains to 1.8008 kg ha⁻¹ in roots, 1.4076 kg ha⁻¹ in shoots, and 0.8192 kg ha⁻¹ in pods. The corresponding control under furrow irrigation showed lower uptake across all tissues and seasons.

Table 5
Effects of interactions between methods of irrigation and soil amendments on uptake of cadmium metal (kg ha⁻¹) in roots, shoots and pods

Treatments	**2021 Short rains**			**2022 Long rains**		
	RUPT	**SUPT**	**PUP**	**RUP**	**SUPT**	**PUPT**
Control Basin	1.3103^{a}	1.0131^{a}	0.0902^{a}	1.8008^{a}	1.4076^{a}	0.8192^{a}
Control Furrow	0.9100^{b}	0.7136^{b}	0.0619^{b}	1.5006^{b}	1.0484^{b}	0.5203^{b}
Fertium Basin	0.9032^{c}	0.6136^{c}	0.0600^{c}	1.3007^{c}	0.9178^{c}	0.5145^{c}
Fertium Furrow	0.6083^{d}	0.4123^{d}	0.0400^{d}	1.0045^{d}	0.6138^{d}	0.3115^{d}
Farmyard Basin	0.6016^{e}	0.4103^{d}	0.0321^{e}	0.9007^{e}	0.6071^{e}	0.2155^{e}
Farmyard Furrow	0.4161^{f}	0.3350^{e}	0.0233^{f}	0.7004^{f}	0.4017^{f}	0.1236^{f}
Gypsum+Farmyard Basin	0.3400^{g}	0.2104^{f}	0.0132^{g}	0.6048^{g}	0.3040^{g}	0.0921^{f}
Gypsum+Farmyard Furrow	0.2132^{h}	0.1027^{g}	0.0065^{h}	0.4000^{h}	0.2924^{h}	0.0083^{g}
Vermicompost Basin	0.2101^{i}	0.0816^{h}	0.0041^{i}	0.3008^{i}	0.0902^{i}	0.0066^{h}
Vermicompost Furrow	0.1019^{j}	0.0524^{i}	0.00214^{j}	0.1104^{j}	0.0624^{j}	0.00331^{i}
P-value	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Means followed by different letter in a column are significantly different at p ≤ 0.05						
PUPT = Pod Uptake; SUPT=Shoot Uptake; SUPT=Root Uptake; Season one (Short rains); season two (Long rains).						

A consistent reduction in cadmium uptake was observed with the application of soil amendments under both irrigation methods. Fertium and farmyard manure treatments showed moderate uptake levels, while the gypsum and farmyard manure combination further reduced cadmium accumulation. The lowest uptake values were consistently observed under vermicompost treatments, particularly when combined with furrow irrigation.

Under vermicompost with furrow irrigation, root uptake decreased to 0.1019 kg ha⁻¹ in the short rains and 0.1104 kg ha⁻¹ in the long rains. Corresponding shoot and pod uptake values were also minimal, with pod uptake recorded at 0.0021 kg ha⁻¹ in the short rains and 0.0033 kg ha⁻¹ in the long rains. Across all soil

amendments, basin irrigation consistently resulted in higher cadmium uptake compared to furrow irrigation within the same treatment category.

3.6 Effects of irrigation method and soil amendments on copper uptake in French bean tissues

Soil amendments had a pronounced effect on copper uptake in all plant tissues. The control treatment consistently recorded the highest uptake values in both seasons (Table 6). In the short rains, shoot uptake reached 2.010 kg ha⁻¹, followed by root uptake at 1.650 kg ha⁻¹ and pod uptake at 0.070 kg ha⁻¹. These values increased further in the long rains, with shoot uptake reaching 2.56 kg ha⁻¹, root uptake 2.17 kg ha⁻¹, and pod uptake 0.20 kg ha⁻¹.

Table 6
Irrigation and soil amendments influence on uptake of copper metal (kg ha⁻¹) in roots, shoots and pods

Factor		**2021 Short rains**			**2022 Long rains**		
	Treatments	**RUP**	**SUPT**	**PUPT**	**RUPT**	**SUPT**	**PUPT**
Soil Amendments	Control	1.650^{a}	2.010^{a}	0.070^{a}	2.17^{a}	2.56^{a}	0.20^{a}
	Fertium	1.210^{b}	1.560^{b}	0.050^{b}	1.55^{b}	1.95^{b}	0.07^{b}
	Farmyard	0.690^{c}	1.010^{c}	0.030^{c}	1.05^{c}	1.46^{c}	0.06^{c}
	Gypsum +farmyard	0.060^{d}	0.620^{d}	0.020^{d}	0.08^{d}	0.95^{d}	0.04^{d}
	Vermicompost	0.020^{e}	0.180^{e}	0.010^{e}	0.06^{e}	0.41^{e}	0.02^{e}
p-value		< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Irrigation	Basin	0.80^{a}	1.25^{a}	0.040^{a}	1.08^{a}	1.60^{a}	0.11^{a}
	Furrow	0.65^{b}	0.90^{b}	0.020^{b}	0.88^{b}	1.33^{b}	0.04^{b}
p-value		< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Means followed by different letter in a column are significantly different at p ≤ 0.05							
PUPT = Pod Uptake; SUPT=Shoot Uptake; SUPT=Root Uptake; Season one (Short rains); season two (Long rains).							

A progressive reduction in copper uptake was observed with the application of soil amendments. Fertium showed lower uptake compared to the control, followed by further reductions under farmyard manure and the gypsum plus farmyard manure treatment. Vermicompost consistently resulted in the lowest copper uptake across all plant tissues, with values as low as 0.020 kg ha⁻¹ in roots and 0.010 kg ha⁻¹ in pods during

the short rains. Similar trends were maintained in the long rains, where vermicompost recorded the lowest uptake in all tissues.

Irrigation method also significantly affected copper uptake. Basin irrigation resulted in higher uptake compared to furrow irrigation across all plant tissues and seasons. In the short rains, basin irrigation recorded shoot uptake of 1.25 kg ha^{-1} compared to 0.90 kg ha^{-1} under furrow irrigation. This pattern was consistent in the long rains, where shoot uptake reached 1.60 kg ha^{-1} under basin irrigation and 1.33 kg ha^{-1} under furrow irrigation. Similar differences were observed in root and pod uptake.

3.7 Interaction effects of irrigation method and soil amendments on copper uptake in French bean tissues

The highest copper uptake was recorded under the control combined with basin irrigation in both seasons. In the short rains, this treatment resulted in root, shoot, and pod uptake values of 1.800, 2.310, and 0.090 kg ha^{-1}, respectively (Table 7). These values increased further in the long rains to 2.311 kg ha^{-1} in roots, 2.717 kg ha^{-1} in shoots, and 0.317 kg ha^{-1} in pods. The corresponding control under furrow irrigation showed consistently lower uptake across all plant tissues.

Table 7
Effects of interactions between methods of irrigation and soil amendments on uptake of copper metal (kg ha^{-1}) in roots, shoots and pods

Treatments	2021 Short rains			2022 Long rains		
	RUPT	SUPT	PUPT	RUPT	SUPT	PUPT
Control Basin	1.800[a]	2.310[a]	0.090[a]	2.311[a]	2.717[a]	0.317[a]
Control Furrow	1.510[b]	1.800[b]	0.060[b]	2.023[b]	2.412b	0.101[b]
Fertium Basin	1.400[c]	1.700[c]	0.050[c]	1.714[c]	2.073[c]	0.094[c]
Fertium Furrow	1.010[d]	1.310[d]	0.040[d]	1.407[d]	1.836[d]	0.086[d]
Farmyard Basin	0.714[e]	1.200[e]	0.040[d]	1.218[e]	1.614[e]	0.065[e]
Farmyard Furrow	0.680[f]	0.820[f]	0.020[e]	0.906[f]	1.314[f]	0.064[e]
Gypsum+Farmyard Basin	0.070[g]	0.720[g]	0.020[e]	0.104[g]	1.113[g]	0.047[f]
Gypsum+Farmyard Furrow	0.050[h]	0.520[h]	0.01[f]	0.082[h]	0.807[h]	0.036[g]
Vermicompost Basin	0.040[i]	0.220[i]	0.009[g]	0.071[h]	0.5411[i]	0.024[h]
Vermicompost Furrow	0.010[j]	0.140[j]	0.007[g]	0.046[i]	0.3128[j]	0.017[i]
p-value	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Means followed by the same letter in a column are not significantly different at p ≤ 0.05						
RUPT=Root Uptake; SUPT=Shoot Uptake; PUPT = Pod Uptake for season 1 (Short rains) and season 2 (Long rains)						

A gradual reduction in copper uptake was observed with the application of soil amendments under both irrigation methods. Fertium and farmyard manure treatments recorded intermediate uptake levels, while the gypsum and farmyard manure combination resulted in further reductions. The lowest copper uptake values were consistently observed under vermicompost treatments, particularly when combined with furrow irrigation.

Under vermicompost with furrow irrigation, root uptake decreased to 0.010 kg ha^{-1} in the short rains and 0.046 kg ha^{-1} in the long rains. Corresponding shoot uptake values were 0.140 and 0.3128 kg ha^{-1}, while pod uptake remained low at 0.007 and 0.017 kg ha^{-1} across the two seasons. Across all soil amendments, basin irrigation consistently resulted in higher copper uptake compared to furrow irrigation within the same treatment category.

4. Discussion

4.1 Effects of irrigation method and soil amendments on lead uptake in roots, shoots and pods

The higher lead uptake observed under basin irrigation can be attributed to the prolonged retention of water within the basins, which likely enhanced soil moisture conditions and promoted greater solubilization of lead in the rhizosphere (Srivastava et al.2022). Increased moisture availability may have facilitated higher transpiration rates, thereby enhancing the movement of dissolved lead ions through the transpiration stream into plant tissues (Selim et al.2023). This observation is consistent with findings from previous studies, where elevated moisture levels were associated with increased lead uptake in crops such as lettuce (Letey et al.2025).

The reduction in lead uptake observed under farmyard manure application can be linked to the formation of stable complexes between organic matter and lead ions, as well as increased adsorption within the soil matrix. These processes likely reduced the availability of lead for plant uptake (Lwin et al.2023). Similar findings have been reported by other researchers, who observed that higher organic matter content enhances the retention of lead in soils, thereby limiting its mobility and uptake by plants (Imran 2024).

Under vermicompost treatment, the notably lower lead uptake may be explained by the presence of functional groups such as carboxylic acids, which facilitate the adsorption of lead ions through proton exchange mechanisms in the soil solution (Mogire et al.2025). In addition, the high organic matter content in vermicompost enhances its sorption capacity, further contributing to the immobilization of lead in the soil (Naik et al.2025).

The combined application of gypsum and farmyard manure also resulted in reduced lead uptake, which may be attributed to improvements in soil structure, enhanced aggregation, and increased adsorption capacity. These changes likely contributed to reduced mobility of lead within the soil system (Sikka et al.2025). Comparable results have been reported in sunflower production systems, where the application of gypsum in combination with organic amendments reduced lead uptake (Vadivel and Pitchamuthu 2019).

The effects observed under fertium treatment may be associated with the supply of calcium ions, which can influence the uptake and transport of lead within plant tissues. Calcium ions may interfere with membrane transport processes, thereby reducing the movement of lead from roots to shoots and pods (Pouya et al.2025).

4.2 Effects of interaction between irrigation method and soil amendments on lead uptake in roots, shoots and pods

The higher lead uptake observed under the interaction of basin irrigation and the control treatment may be attributed to reduced oxygen availability in the soil due to prolonged water retention. Such conditions are likely to alter soil chemical properties, leading to increased solubility of lead and enhanced availability for plant uptake (Li et al.2016). This observation is consistent with findings from other studies that reported similar increases in lead uptake under waterlogged conditions (Tang et al.2022).

The interaction between basin irrigation and farmyard manure may be associated with the increased supply of organic matter, which contributes to the formation of organic acids. These compounds can enhance the solubility of lead in the soil solution, thereby increasing its availability within the rhizosphere (Osmolovskaya et al.2018). Similar observations have been reported in previous studies (Verma et al.2023).

The combined effect of farmyard manure and gypsum may be explained by the simultaneous contribution of calcium, sulfur, and organic matter to the soil system. These components can promote the formation of lead compounds such as sulfates and stable complexes, thereby influencing lead dynamics in the soil and plant system (Jia et al. 2024).

The interaction between basin irrigation and vermicompost may be attributed to the moisture-retaining nature of basin irrigation, which can facilitate the breakdown of lead-containing compounds and increase the release of lead ions into the soil solution (Goswami et al.2015). This finding is in agreement with earlier reports that highlighted similar interactions between moisture conditions and organic amendments in influencing metal availability (Muktamar et al.2023).

4.3 Effects of irrigation method and soil amendments on cadmium uptake in roots, shoots and pods

The higher accumulation of cadmium in root tissues compared to shoots and pods can be attributed to its sequestration within root vacuoles and limited translocation to aerial parts. Cadmium is often chelated and retained within the vacuolar compartments of root cells, which restricts its upward movement through the xylem (Ngugi et al.2022). In addition, structural barriers such as lignified casparian strips in the endodermis further limit the transport of cadmium from roots to shoots, thereby contributing to its higher concentration in belowground tissues (Zhang et al.2022).

The reduced cadmium uptake observed under furrow irrigation may be associated with increased salinity conditions, which could enhance the presence of competing ions such as chloride. These ions may interact with cadmium in the soil solution, thereby reducing its availability for plant uptake (Schück and Greger 2023). Similar findings have been reported by other researchers (Boynukisa et al.2023).

The effect of fertium on cadmium uptake can be explained by the role of calcium ions in the soil. Calcium competes with cadmium for uptake sites and helps maintain the integrity of plant cell membranes, thereby limiting cadmium entry into plant tissues (Lin et al.2020). This observation is consistent with previous findings showing reduced cadmium uptake in soils enriched with calcium (Ye et al.2019).

The higher cadmium uptake observed under the control treatment may be attributed to the elevated availability of cadmium in untreated soils. Excess cadmium can disrupt cell membrane structure and function, leading to increased permeability and greater accumulation within plant tissues (Masood et al.2022). Similar trends have been reported in studies examining cadmium toxicity in plants (Azizi et al.2020; Benavides et al.2005).

The reduction in cadmium uptake under vermicompost treatment may be linked to the presence of functional groups such as hydroxyl and phenoxyl, which can bind cadmium ions and form stable

complexes. This process reduces the bioavailability of cadmium in the soil and limits its uptake by plants (Sohail et al.2019). Comparable results have been reported in pepper crops grown under vermicompost application (Altmayer et al.2021).

The combined application of farmyard manure and gypsum may have reduced cadmium uptake through interactions between calcium and cadmium ions, which compete for uptake sites. In addition, the increase in cation exchange capacity enhances the retention of cadmium on soil exchange sites, thereby limiting its movement into plant roots (Naveed et al.2021). This observation agrees with earlier findings on the role of gypsum and organic amendments in reducing cadmium uptake (Rehman et al.2018).

Under farmyard manure treatment, reduced cadmium uptake may be attributed to the dilution effect of organic matter and competition for adsorption sites within the soil matrix. The presence of organic matter increases the number of binding sites, which can retain cadmium and reduce its availability for plant uptake (Nyambaka et al.2014). Similar reductions in cadmium uptake under farmyard manure application have been reported by other authors (Khalid et al.2017).

4.4 Effects of interaction between irrigation method and soil amendments on cadmium uptake in roots, shoots and pods

The higher cadmium uptake observed under the interaction of basin irrigation and the control treatment may be attributed to increased metal solubility under conditions of excess moisture. The prolonged retention of water in basins likely created saturated soil conditions that enhanced cadmium availability in the rhizosphere, thereby increasing its uptake by plants (Huang et al.2024). This observation is consistent with findings from other studies that reported increased heavy metal accumulation in vegetables such as spinach under similar conditions (Syed et al.2023).

The interaction between fertium and furrow irrigation may be associated with the increased availability of calcium, which promotes root development and enhances water uptake while simultaneously reducing cadmium accumulation. The presence of calcium may have contributed to competitive inhibition of cadmium uptake, thereby lowering its accumulation in plant tissues (Rassaei et al.2020). This finding aligns with previous studies on cadmium accumulation dynamics in plants (Zhang et al.2020).

The contrasting responses observed under vermicompost and basin interaction may be linked to the interaction between moisture conditions and organic matter. The increased moisture may have facilitated the release and redistribution of cadmium within the soil solution (Castellini et al. 2024). In contrast, the combination of vermicompost and furrow irrigation likely enhanced the immobilization of cadmium through adsorption and binding processes, thereby limiting its availability for plant uptake (Nedjimi 2021). Similar observations have been reported in studies examining cadmium behavior in contaminated soils (Mamun et al.2021).

The reduction in cadmium uptake observed under farmyard manure treatments may be attributed to the role of organic matter as a sink for cadmium, where adsorption processes limit its mobility and availability in the soil (Hamid et al.2018). This observation is consistent with findings from other studies that reported

reduced cadmium uptake following the application of organic amendments in crop production systems (Chattha et al.2021).

The interaction between farmyard manure and furrow irrigation may further enhance this effect through improved nutrient cycling and controlled water distribution. These conditions may have reduced cadmium availability in the soil solution while supporting plant growth and development (Elgharably 2020). Comparable findings have been reported in studies involving wastewater irrigation and gypsum amendments in dark cumin production systems (Rahimi et al.2021).

4.5 Effects of irrigation method and soil amendments on copper uptake in plant tissues

The higher accumulation of copper in shoot tissues compared to roots and pods may be attributed to enhanced cambial activity and translocation processes within the plant. The development of additional cambium cells in shoots facilitates the movement and storage of copper, leading to greater accumulation in aerial tissues (Zand and Mühling, 2022). This observation is consistent with previous studies that reported preferential accumulation of copper in shoots due to internal transport dynamics and tissue-specific partitioning (Atta et al.2023).

The elevated copper uptake observed under the control treatment may be linked to the inherent soil conditions, particularly increased alkalinity, which can influence copper solubility and availability in the soil solution. Under such conditions, copper exists in forms that are more readily taken up by plants, resulting in higher accumulation in plant tissues (Golia et al.2023). Similar findings have been reported under saline environments where copper availability and uptake were enhanced (Drzewiecka et al.2025).

Lower copper uptake under furrow irrigation compared to basin irrigation may be explained by differences in soil moisture distribution and salinity dynamics. Furrow irrigation is likely to create localized zones of higher salinity, which may have influenced water movement reducing copper uptake by limiting its availability in the root zone (Chrysargyris et al.2019). This observation agrees with previous studies on the influence of irrigation regimes on nutrient and metal uptake in crops such as buckwheat (Ullah et al.2025).

The reduced copper uptake observed under farmyard manure treatment may be attributed to the presence of humic substances, which may have played role in binding of copper ions converting them into less available forms in the soil. This immobilization process limits copper uptake by plants (Hussain et al.2021). Similar reductions in copper uptake following farmyard manure application have been reported in other studies (Toby et al.2025).

The lowest copper uptake recorded under vermicompost treatment may be associated with increased microbial activity in the soil. Soil microorganisms contribute to the formation of stable organic complexes that immobilize copper, thereby reducing its bioavailability and uptake by plants (Auccahuasi and Mandujano, 2024). This finding aligns with previous reports highlighting the role of microbial processes in regulating metal availability under vermicompost application (Paucara et al.2024).

The combined application of gypsum and farmyard manure may have further reduced copper uptake through the formation of copper sulfides and competitive interactions between calcium and copper ions at uptake sites. These processes likely limited copper mobility and availability in the soil (Awasthi et al.2020). Comparable findings have been reported in studies examining the role of gypsum-based amendments in regulating copper uptake (Kebede et al.2021).

4.6 Effects of interaction between irrigation method and soil amendments on copper uptake in roots, shoots and pods

The higher copper uptake observed under the interaction of basin irrigation and the control treatment may be attributed to prolonged presence of water in basin irrigation enhancing the dissolution and mobility of copper in the soil, making it more available for plant uptake compared to the corresponding furrow irrigation treatment (Tudi et al.2024). This observation is consistent with findings from other studies that demonstrated the influence of water regimes on copper uptake by plant roots (Pampinella et al.2025).

The reduced copper uptake under the combined application of farmyard manure and gypsum may be explained by multiple interacting processes. Elevated salinity conditions may have limited moisture availability, while increased adsorption of copper onto soil colloids reduced its mobility (Wei et al.2020). In addition, the supply of calcium ions likely enhanced cation exchange capacity, providing more binding sites for copper and thereby reducing its availability in the rhizosphere (Irin and Hasanuzzaman 2024). Similar findings have been reported in studies examining the influence of organic matter on copper dynamics in soils (Obaid et al. 2023).

The interaction between furrow irrigation and farmyard manure may have contributed to reduced copper uptake through flocculation processes that may have enhanced the retention of copper within the soil matrix, while organic matter facilitated the complexation of copper ions, thereby limiting their availability for plant uptake (Rani and Singh, 2022). This finding aligns with previous studies on the role of farmyard manure in regulating copper mobility in bean production systems (Akhtar et al. 2023).

The interaction between fertium and furrow irrigation may be attributed to competitive interactions between calcium and copper ions at uptake sites within the plant limiting copper transport through the xylem, while interactions with salts in the furrow environment may have further reduced copper availability (Moukhtari et al. 2025). This observation is supported by earlier findings on nutrient competition and metal uptake dynamics (Marschner 2012).

The reduced copper uptake observed under the interaction of furrow irrigation and vermicompost may be associated with the role of organic compounds in enhancing copper complexation within the soil. These complexes reduce the bioavailability of copper, thereby limiting its uptake by plants (Karimi et al. 2020). Similar results have been reported in studies highlighting the immobilization of copper under vermicompost application (Khedr et al. 2019).

5. Conclusion

This study demonstrated that both irrigation method and soil amendments significantly influence the uptake of cadmium, lead, and copper in French bean under contaminated irrigated soils. Across the two cropping seasons, heavy metal accumulation consistently followed the order roots > shoots > pods, indicating limited translocation to edible parts but substantial accumulation in belowground tissues.

Basin irrigation generally resulted in higher uptake of all three metals compared to furrow irrigation, likely due to increased soil moisture and enhanced metal solubility. In contrast, furrow irrigation reduced metal uptake, suggesting its suitability as a management practice in contaminated environments.

Among the soil amendments, vermicompost was the most effective in reducing the uptake of cadmium, lead, and copper across all plant tissues. This effect can be attributed to enhanced metal immobilization through organic matter interactions and microbial activity. Farmyard manure and the gypsum plus farmyard manure combination also reduced metal uptake, although to a lesser extent, while the control treatment consistently recorded the highest accumulation.

The interaction effects further revealed that combining vermicompost with furrow irrigation provided the greatest reduction in heavy metal uptake, highlighting the importance of integrated soil and water management strategies. These findings demonstrate that appropriate amendment selection and irrigation practices can effectively mitigate heavy metal transfer into crop tissues.

Generally, the study provides practical evidence that vermicompost application combined with furrow irrigation can serve as a sustainable phytomanagement strategy for reducing heavy metal uptake in French bean production systems under contaminated irrigation conditions. This approach has significant implications for improving food safety and supporting safe crop production in areas affected by heavy metal pollution.

Declarations

Ethics Approval

This is not applicable.

Consent to participate

This is not applicable.

Consent to publish

This is not applicable.

Competing interests

The authors declare they have no known competing financial interest or personal relationships to report regarding the present study.

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Author Contribution

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Availability of Data and Materials

The authors confirm that the data supporting the findings of this study are available within the article [and/or] its Supplementary Materials.

Data availability statement

All data generated or analyzed during this study are included in this published article (and its supplementary information files).

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