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Geospatial Distribution and Potential Risk Assessment of Cadmium and Nickel Contamination in Al Fayoum Soils, Egypt

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THIS STUDY presents a comprehensive risk assessment of cadmium (Cd) and nickel (Ni) contamination in agricultural soils of Al Fayoum Governorate, Egypt, through an integrated approach that combines geochemical analysis with GIS technique. 125 soil and 25 plant samples were collected from the top 30 cm layer and analyzed for Cd, Ni, and soil properties. Results revealed significant spatial variability, with Cd exceeding the FAO criteria limit in 44.6% of soils and Ni surpassing thresholds in 64.9% of samples. Spatial analysis identified distinct contamination hotspots in Al Fayoum and Itsa districts, which were strongly correlated with the uses of illegal water from some drainage canals and excessive phosphate fertilizer application. The study employed multiple contamination indices (Igeo, CF, TF, BF) and advanced geostatistical techniques, including Inverse Distance Weighting (IDW) interpolation, to develop a composite Soil Quality Index (SQI) based on four main quality indices: chemical, physical, productivity and pollution indices. Notably, the geoaccumulation index (Igeo) showed extreme Ni pollution (Class 6) and moderate-to-strong Cd contamination (Class 4-5), while contamination factors reached 14.7 for Cd and 8.3 for Ni, in wheat crops, demonstrated effective metal exclusion mechanisms (TF<1, BF<0.9), suggesting limited food chain transfer despite soil contamination. Risk mapping classified 90% of the area as low to medium risk, with clear north-south quality gradients. These findings offer a replicable framework for monitoring heavy metal pollution in arid agricultural regions globally, emphasizing the urgent need for policy interventions to control pollution sources and protect food safety.

Keywords: Heavy metals, Pollution Indices, Soil contamination, Sustainable agriculture, GIS, Soil quality.

Introduction

The accumulation of heavy metals in soil poses a significant environmental concern due to their toxicity, persistence, and potential infiltration into the food chain (Zhao *et al.,* 2022). Globally, various activities, including the overuse of phosphate fertilizers, traffic emissions, pesticides, industrial chemicals, and unregulated wastewater irrigation, have exacerbated soil pollution in recent decades, threatening crop productivity and food safety by absorb metals and accumulate it in easily harvestable parts (Chibuike and Obiora, 2022) and Rahma *et al.,* (2024). The elevated levels exceed permissible limits, estimated at 0.8 mg/kg^{-1} for cadmium and 40 mg/kg^{-1} for nickel (FAO, 2006). Exceeding these concentrations can encourage chlorosis, disrupt nutrient uptake, impair microbial activity, reduce soil fertility due to non biodegradability and diminish crop yields. **In severe cases, plant productivity may decline** by ≥ 20%, which compromises both food security and economic sustainability (Ansari *et al.,* 2022). Additionally, excessive levels in the soil can increase the risk of developing lung, nose, and skin cancers (Coradduzza *et al.,* 2024). As a result, the United Nations Environment Assembly adopted resolution UNEA-3 to manage and address soil pollution. This decision underscores the international recognition that soil pollution has now become a global concern to mitigate the impacts of this significant threat (Rodríguez-Eugenio *et al.,* 2018). By virtue of the United Nations Assembly decree, several researchers in different parts of the world have attempted to investigate and observe soil contamination in various areas, especially those facing agriculture challenge by water scarcity and soil limitations (El-Hassanin *et al.,* 2025). In Al Fayoum

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Governorate (which includes five districts), Egypt, this situation is exacerbated by the misuse of inorganic fertilizers and irrigation with illegal water from some drainage canals (Ahmed, 2019), leading to alarming accumulations of Cd and Ni in soils. Abdurrahman (2020) reported that in the top layers of Al Fayoum District, the total concentrations of Cd ranged from 15.5 and 215 mg/kg^{-1}. In Senouris District, for the upper 30 cm, the total concentrations of Cd varied between 0.016 and 1.280 mg/kg^{-1}. Ahmed (2019) reported that Cd concentrations in Ibsheway District were approximately 0.123 and 4.115 mg/kg^{-1}. On the other hand, Abdurrahman (2020) reported that Ni contents in Al Fayoum District soils ranged from 5 to 489.5 mg/ kg^{-1}, while Abd El-Aziz *et al.,* (2025) found Ni levels exceeding 50 mg/ kg^{-1}.

Despite identifying these risks in these districts, critical gaps remain in the available information about the entire region of Al Fayoum Governorate regarding the distribution of cadmium and nickel and methods to identify them. Most research and the previously mentioned studies focus on soil and water pollution distribution (Bouslihim *et al.,* 2021), neglecting the relationship between soil properties and pollution indices on spatial patterns, translocation mechanisms, and localized contamination drivers of these metals. Presently, several contamination indices and methods for assessing soil contamination exist, such as the geoaccumulation index (Igeo), which reflects the effects of human activities on heavy metal accumulation, the contamination factor, which identifies deteriorated areas requiring immediate remediation (Youssef *et al.,* 2024), the translocation factor, which identifies the ability to transfer metals from roots to edible parts, critical for assessing food chain risks (Asmaa *et al.,* 2023), and the bioaccumulation factor, which evaluates soil-to-plant metal uptake efficiency, informing crop selection in polluted areas (Karimi *et al.,* 2020). To address these gaps, this research was conducted.

This research aims to investigate and map the distribution of Cd and Ni across the soils of Al Fayoum Governorate, evaluate contamination levels based on soil properties and pollution indices, and produce a soil quality and suitability map of Al Fayoum by integrating geochemical and GIS techniques. This study provides a scientific foundation for policymakers to enforce soil remediation strategies and sustainable farming practices in Egypt, aligning with global efforts to alleviate the risks of soil pollution.

Materials and Methods:

Study area

Al Fayoum Governorate is located in the western part of Egypt, approximately 90 kilometers from Cairo. The geographic coordinates are in UTM zone 36, with a latitude ranging from 29° 05′ N to 29° 35′ N and a longitude from 30° 20′ E to 31° 05′ E (**Fig. 1**). It encompasses an area of 6,068 km², divided into five districts: Al Fayoum, Senouris, Ibsheway, Atsa, and Tamyah District, with a total cultivated area of 324,000 feddans. Al Fayoum Governorate is connected to the Nile River by Bahr Yousef, which delivers Nile water to the region (**El Zeiny and Effat, 2017**).

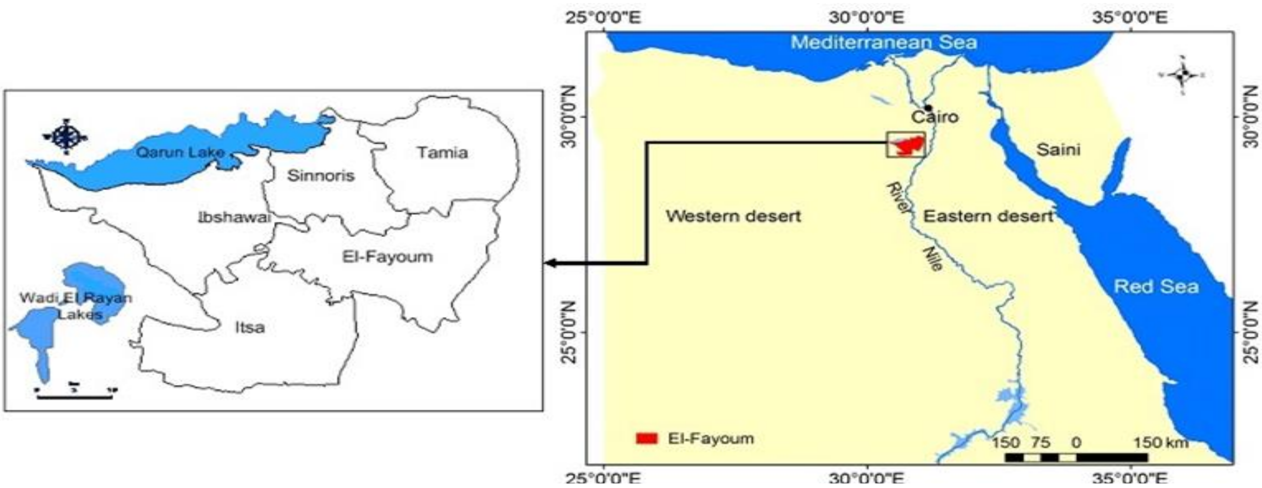

Fig. 1. Location of Al Fayoum governorate in Egypt.

Field Study and samples Analysis

A random field survey was conducted across the cultivated soils of Al Fayoum Governorate, Egypt, with sampling sites spaced approximately 1.5 km apart to ensure representative coverage of the studied area boundaries and land features. Accordingly, one hundred twenty-five soil samples were collected from different sites, covering the spatial variability of Al Fayoum agricultural soils, alongside 25 plant samples from selected sites for complementary analysis. Soil samples were taken from the surface soil layer (0-30 cm), reflecting the plow zone where heavy metal accumulation and root uptake are most critical. The exact positions of the sample points were identified by GPS (Fig. 2). The collected soil samples were dried, crushed, and passed through a 2 mm sieve to obtain fine soil.

Soil electrical conductivity was assessed using a conductivity meter in soil paste extract. Soil pH was measured with a pH meter in a soil suspension at a 1:2.5 soil-water ratio (FAO, 2020a). The percentage of calcium carbonate was determined using Scheibler's volumetric calcimeter (FAO, 2020b). The percentage of organic carbon was estimated using the dichromate oxidation method according to Walkley and Black (FAO, 2020c).

To measure the concentrations of cadmium and nickel metals, 0.25 g of soil samples was digested using a microwave at 200 °C, then treated with aqua regia (3:1 concentrated $HCl:HNO_3$) (FAO, 2022). Oven-dried plant samples at 70 °C were ground, and 0.5 g of each sample was digested using a mixture of sulfuric acid and perchloric acid (Helmy and Shaban, 2013).

Assessment of Contamination

The Geo-accumulation index (Igeo)

The Geo-accumulation Index (Igeo), developed by Muller, (1981) has proven to be a valuable tool for predicting soil pollution and assessing the extent of metal pollution in an area by comparing current metal concentrations with pre-existing background levels. This index is based on the following equation:

$$geo = \log_2 X \frac{C_n}{1.5\, B_n} \quad \text{(Eq. 1)}$$

Where; Igeo is the Geo-accumulation index, C_n is element concentration in the sample, and the biogeochemical background value provided by Liao and Chao, 2004, is a constant of 1.5, which helps to analyze natural natural fluctuations in the content of a given substance and minimal anthropogenic, influences and B_n is background value. Buccolieri etal. (2006) have classified classes of Igeo as shown in (Table 1).

Contamination Factor (C.F)

The Contamination Factor was described by Hakanson, (1980) to calculate the contamination level, as detailed in the following equation. This equation involves dividing the metal concentration in the soil by the corresponding background value, as reported by Turekian and Wedepohl (1961).

$$C.F = con_{measured} / con_{background} \quad \text{(Eq. 2)}$$

Where C.F is contamination factor, $con_{measured}$ is the concentration metal in the contaminated soil and $con_{background}$ is the background metal concentration. The categories of C.F are described as shown in (Table 1).

Translocation Factor (TF)

It refers to the mobilization ratio to identify heavy metal translocation from soil to root and shoot systems; this index provides a quantitative interpretation of the relative differences in the biological availability of metals to plants. (Ramírez *et al.,* 2021).

Gupta *et al.,* (2021) reported the concentration of metals in the corresponding shoot or root as shown in (Table 1) where value of less than 1 indicates that the plant has the potential for phytostabilisation, where the metal is immobilized in the roots, preventing it from being translocation to the shoots. The following equation indicates the ability to accumulate in plants from contaminated soil.

$$\mathbf{TF} = \mathbf{C}_{shoot} / \mathbf{C}_{root} \quad \text{(Eq. 3)}$$

Where TF is Translocation Factor, C_{shoot} and C_{root} represent the heavy metal concentrations in the plant's shoot and root.

Bioaccumulation Factor (BF)

It is a good measure for understanding accumulation of heavy metals from soil into the edible parts of plants, which can be useful for assessing the safeness of consuming food crops grown in contaminated soil (Aziz *et al.*, 2023). It is calculated according to different classes (Table 1) as a result of Equation 4, illustrated by Radulescu *et al.*, (2013), as:

$$BF = \mathbf{C}_{plant} / \mathbf{C}_{soil} \quad \text{(Eq. 4)}$$

Where BF is bioaccumulation factor, C_{plant} is the heavy metal concentration in plant sample (mg/kg), C_{soil} is the heavy metal concentration in soil sample (mg/kg^{-1}).

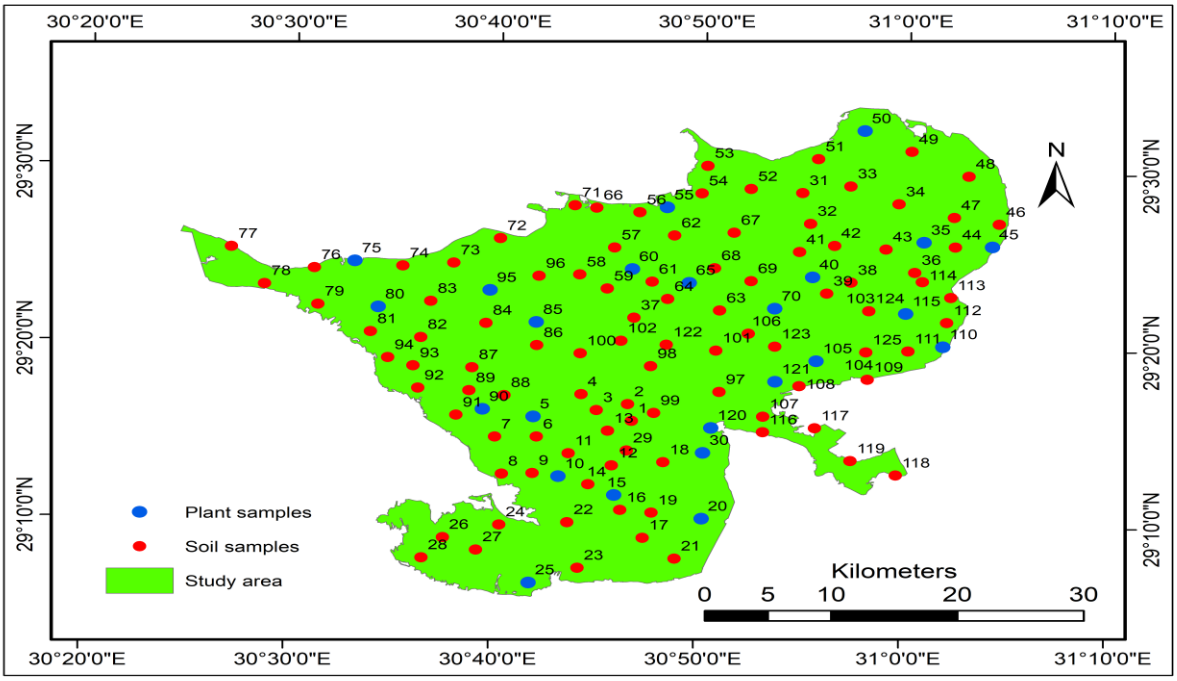

Fig. 2. Location of selected samples in Al Fayoum Governorate .

Spatial Distribution Analysis and potentiality Map

The spatial distribution maps of soil were created using the Inverse Distance Weighting (IDW) interpolation method to identify various properties such as ECe, pH, OC, and $CaCO_3$, as well as selected soil heavy metals like cadmium (Cd) and nickel (Ni) contamination across Al Fayoum soils. The IDW method is widely used when data are collected in multiple locations to produce continuous information and for its ability to model pollution gradients from point sources where concentrations decrease with distance (Ali and Moghanm, 2013). With 125 systematically sampled points (spaced ~1.5 km apart), each grid prediction weighted the 12 nearest neighbors using a power function ($1/distance^2$), giving greater influence to proximate measurements (Azpurua and Ramos, 2010). The resulting maps directly informed contamination hotspot identification when cross-referenced with pollution indices (Igeo, CF, EF and BF) and land-use data, demonstrating IDW's suitability for assessing heavy metal risks in anthropogenically impacted arid agricultural systems like Al Fayoum (Abowaly *et al.*, 2021)

The Soil Potentiality Map of Al Fayoum Governorate is a comprehensive assessment of soil quality and its suitability for proposed land uses. This map was developed by integrating multiple evaluated soil indicators within a Geographic Information Systems (GIS) framework (Ahmed *et al.*, 2021). The Potentiality map was generated by reclassifying the values of each indicator (or parameter) into four classes according to FAO, (2006). The potentiality maps were constructed using easy-to-estimate indicators with their weighted percentages, as shown in (Table 1) (Demenois *et al.*, 2017), A score ranging from 1.0 to 0.2 was assigned for each parameter, while a score of 0 was given to unclassified areas (Ahmed *et al.*, 2021). To calculate the four quality indices, the following equation was used:

$$Index_x = (S1\ X\ S2\ X\ \ldots..)^{1/n}$$

Where X is the quality index, S is the score of the parameter, and n is the number of parameters (Ahmed *et al.*, 2021). By combining several indicators to produce four stability maps, the first map was soil chemical quality map, this map evaluates some physical and chemical properties of the soil, such as soil EC, soil pH, soil $CaCO_3$, and soil organic matter, that influence soil stability and suitability for various land uses (Bashir *et al.*, 2021). The second one was soil physical quality map considers topographic features like slope, elevation, and aspect, which affect soil erosion, water retention, and overall stability (Amare *et al.*, 2024). The third map was soil fertility quality map assesses the soil's ability to support agricultural or other productive land uses (Mert *et al.*, 2020), and the final map was soil pollution indices quality map integrates various soil indices like Geo-accumulation index, Contamination, Bioaccumulation, and Translocation Factors to provide a holistic view of soil health and stability (Odat, 2015) , (Fig. 3). In addition two separate soil environmental fertility maps were created to show the distribution of both cadmium and nickel heavy metals in the soil samples.

Table 1. Dataset included soil parameters evaluation.

Indicator	Description	Threshold	Score	% Weight	Reference
Chemical quality CQ = (ECe XpH X $CaCO_3$X OM **)** ¼					
ECe dS/m^{-1}	Non-saline	<2	1	26	FAO, 2020a
	Slightly saline	2-4	0.8		
	Moderately saline	4-8	0.6		
pH	Slightly alkaline	7.4–7.8	1	29	FAO, 2020a
	Moderately alkaline	7.9–8.4	0.8		
	Strongly alkaline	8.5–9.0	0.6		
$CaCo_3$ g kg^1	Low content	<6%	1	28	bFAO, 2020
	Slight content	6-12%	0.8		
	Moderately content	12-20%	0.6		
	High content	20-40%	0.4		
Organic matter g kg^1	Extremely low	<0.25 %	1	17	cFAO, 2020
	Very low	0.25-0.75 %	0.8		
	Relatively low	0.75-1.50 %	0.6		
	Low	1.50-3 %	0.4		
Physical quality PQ = (DEM X Slope X Aspect XCurvature)¼					
Slop	Very gently sloping	< 2	1	35	FAO, 2006
	Gently sloping	2–5	0.8		
	Sloping	5–10	0.6		
	Strongly sloping	10-15	0.5		
	Moderately steep	15-30	0.4		
	Steep	>30	0.2		
Aspect	Flat	1	1	15	FAO, 2006
	North	0-22.5	0.9		
	Northeast	22.5-67.5	0.8		
	East	67.5-112.5	0.7		
	Southeast	112.5-157.5	0.6		
	South	157.5-202.5	0.5		
	Southwest	202.5-247.5	0.4		
	West	247.5-292.5	0.3		
	Northwest	292.5-337.5	0.2		
	north	>337.5	0.2		
curvature	+ve value	> 0	1	12	FAO, 2006
	-ve value	< 0	0.6		
	Zero	0	0.2		
DEM		-56 - -25.5	1	38	FAO, 2006
		-25.5 - -8.1	0.8		
		-8.1 – 4.7	0.6		
		4.7 – 14.7	0.4		
		14.7 - 70	0.2		
Soil productivity quality PSQ = (Land-Use × NDVI)$^{1/2}$					
Land-Use	Plant		1	50	FAO, 2006
	Development		0.6		
	Barren		0.2		
NDVI	High density		1	50	FAO, 2006
	Moderate density		0.6		
	Slight density		0.4		
	No vegetation		0.2		
Geo-accumulation index	Uncontaminate	Igeo≤0	1	60	Buccolieri et al. (2006)
	Un-contaminate - Moderate contaminate	0<Igeo<1	0.8		
	Moderate contaminate	1<Igeo<2	0.6		
	Moderate - strong contaminate	2<Igeo<3	0.5		
	strong contaminate	3<Igeo<4	0.4		

	strong -Extreme contaminate	4<Igeo<5	0.3		
	Extreme contaminate	Igeo≥5	0.2		
Contamination Factor	Low contaminate	< 1	1	40	Hakanson (1980)
	Moderate contaminate	1 ≤ 3	0.7		
	Consider contaminate	3 ≤ 6	0.5		
	Very high contaminate	> 6	0.2		
Bioaccumulation Factor	Low Mobility	< 1	1		Radulescu et al. (2013)
	high Mobility	> 1	0.2		
Translocation Factor	can be accumulators	> 1	1		Gupta et al. (2021)
	no influences	= 1	0.6		
	can be an excluder	< 1	0.2		
Environmental Soil Quality,ESQ					
Soil Cd	Uncontaminated	0-0.25	1		FAO, 2022
	Light contamination	0.25-0.8	0.7		
	Contamination	0.8-1.5	0.5		
	High contaminated	> 1.55	0.2		
Soil Ni	Uncontaminated	0-25	1		FAO, 2022
	Light contamination	25-35	0.7		
	Contamination	35-45	0.5		
	High contaminated	> 45	0.2		
Chemical quality CQ	No Risk	<1	1	30	Hussein et al., 2023
	Low Risk	1-2	0.7		
	Medium Risk	2-3	0.5		
	High Risk	>4	0.2		
Physical quality PQ	No Risk	<1	1	12.5	Hussein et al., 2023
	Low Risk	1-2	0.7		
	Medium Risk	2-3	0.5		
	High Risk	>4	0.2		
Productivity quality PSQ	No Risk	<1	1	12.5	Hussein et al., 2023
	Medium Risk	1-2	0.6		
	High Risk	2-3	0.2		
pollution indices quality ISQ	No Risk	<1	1	15	Abdellatifet al., 2021
	Low Risk	1-2	0.7		
	Medium Risk	2-3	0.5		
	High Risk	>4	0.2		
Environmental SQEQuality				30	FAO, 2022

The weight value was assigned to each parameter on the basis of the communality of each indicator calculated by means of mathematical statistics of factor analysis (IBM, SPSS Statistics 19.0). The weight value for each parameter was determined as a ratio of its communality in relation to the overall communality (Yang *et al.*, 2024).
In this study, all quality maps were calculated based on the geometric mean algorithm of indicator scores (Hussein *et al.*, 2023) as follows:

Chemical quality, $CSQ = (pH \times EC \times OM \times CaCO_3)^{1/4}$
Physical quality, $PSQ = (Slop \times Aspect \times Curvature \times DEM)^{1/4}$

Fertility quality, $FSQ = (Land\text{-}Use \times NDVI)^{1/2}$
Indices quality, $ISQ = (Geo\text{-}accumulation\ index \times ContaminationFactor)^{1/2}$

Table 2. classes of soil Potentiality.

Indicator	Value	Class
Soil Potentiality	1	No Risk
	2	Low Risk
	3	Moderate Risk
	4	High Risk

The overlay soil quality map (OSQ) was calculated by combination of these Parameters which increases agronomic productivity and reach to management systems (Rehab *et al* ., 2022) as follows:

$OSQ = [CSQ \times PSQ \times FSQ \times ISQ \times (Cd/or/Ni)/ESQ]^{1/5}$

The sustainability was synthesized using weighted overlay analysis in Arc GIS software, to produce a final Soil Potentiality map that classifies the studied area as high, medium, and low risk for contamination according to the Jenks's natural breaks classifier (Jenks, 1976), and Abdellatif *et al.*, (2021). The used Soil Quality classes are shown in (Table 2). This map can be used as a guide for land-use planning to provide a detailed assessment of soil quality, stability, crop selection, remediation priorities, and suitability for proposed land uses.

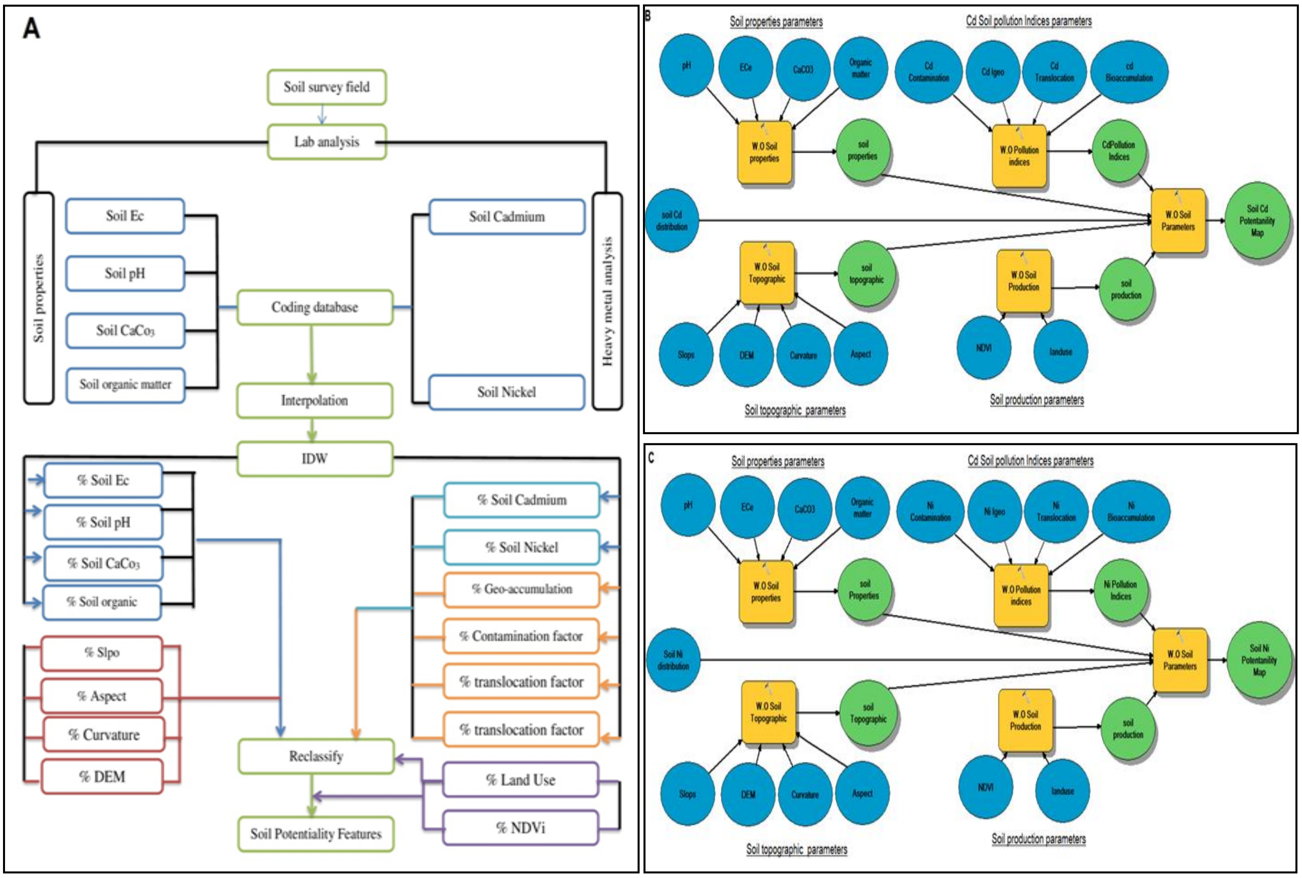

Fig. 3. A Methodological Flowchart and GIS steps, (B) Cadmium soil potentiality map model and (C) Nikel soil potentiality map model.

Results

Cadmium levels and distribution

The total Cadmium concentration in the studied soils ranged between 0.06 and 4.51 mg/kg^{-1}. Accordingly, cadmium distribution exhibited that, in general, the surface layer (0 – 30 cm) of Al Fayoum cultivated area, was described as High Contamination > 1.55 mg/kg^{-1} in Al-Fayoum and Itsa districts

5.4% of the studied soils were uncontaminated (0–0.25 mg/kg^{-1}), 39.7% of the studied soils showed light contamination (0.25–0.80 mg/kg^{-1}), 10% of the studied soils were contamination (0.80–1.5 mg/kg^{-1}), and 44.6% of the studied soils were highly contaminated (>1.55 mg/kg^{-1}) (Figure 4). The Tamyah, Seniors, and Ibsheway districts, were predominantly light contamination, with an area

enclosed 93.7%, 35.1%, and 64.1% of their respective areas. On the other hand, the highest Cd levels were recorded in Itsa and Al Fayoum districts, with 98.7% and 88.8% of their areas classified as high contamination (Table 3).

Nickel levels and distribution

Total Nickel concentration in the surface layer (0 – 30 cm) of Al Fayoum Governorate revealed concentrations ranging from 11.15 to 88.5 mg/kg^{-1}, with levels classified into four contamination categories: uncontaminated soils (0-25 mg/kg^{-1}) covering 5.4% of the total area, light contamination

(25-35 mg/kg^{-1}) occupying 29.6% of the total area, contamination of (35-45 mg/kg^{-1}) comprising 43.2% of the total area; and eventually, high contamination (> 45 mg/kg^{-1}) covering 21.7% of the total (Figure 4). High amount of Ni pollution exceeding the critical limit (≥ 35 mg/kg^{-1}), were observed in Seniors and Al Fayoum districts, covering 85% of their areas. In contrast, uncontaminated and light-contaminated soils (below the critical limit, ≤ 35 mg/kg^{-1}), were more prevalent in Atsa, Tamyah, and Ibsheway districts, covering 57%, 52%, and 31% of their areas, respectively (Table 3).

Table 3. The % value and area by feddans/thousands for Total Cd and Ni in the study area.FAO,(2006).

		Tamya		Sanoris		Ibshway		Itsa		Fayoum		Total area	
		Area	**%**	**Area**	**%**	**Area**	**%**	**Area**	**%**	**Area**	**%**	**Area**	**%**
Uncontaminated	**Cd**	158	0.2	19.6	34.2	2.2	2.2	0	0	0	0	23.8	5.4
	Ni	0	0	0	0	411	0.4	20.1	20.1	106	1.1	23.8	5.4
Light contamination	**Cd**	74.4	93.7	30.5	53.1	65.9	64.1	211	0.2	145	1.5	175.6	39.7
	Ni	41.401	52.1	4.6	8	31.5	30.7	36.6	36.6	12.7	13.2	130.9	29.6
Contamination	**Cd**	4.529	5.7	5.2	9.1	25.5	24.8	951	0.9	9.2	9.6	44.2	10
	Ni	36.721	46.2	43.1	75	44.9	43.7	28.7	28.7	34.0	35.2	191.1	43.2
High contaminated	**Cd**	1.58	0.2	1.9	3.4	8.8	8.6	104.3	98.7	85.9	88.8	197.3	44.6
	Ni	1.1	1.5	9.7	16.9	25.7	25	14.3	14.3	48.6	50.3	96.01	21.7

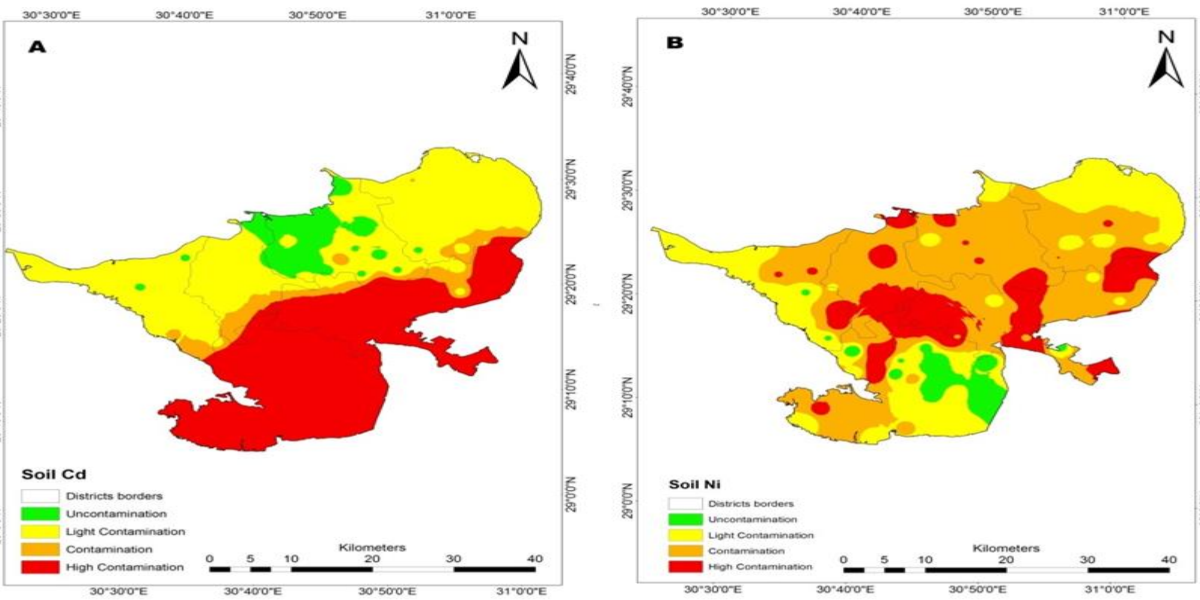

Fig. 4. The distribution of soil heavy metals in the study area top soil (0-30 cm). (A) soil Cd, (B) soil Ni.

The Geo-accumulation index (Igeo)

The Igeo values of cadmium and nickel in the studied area revealed significant contamination levels (Fig 5), with Cadmium having a wide diversity ranging between -1.32 and 4.91 from uncontaminated soils with Igeo ≤ 0 present only in 8 sites in Sinories and Ibshway districts, to extremely contaminated in Itsa and Al Fayoum districts (Class 4-5), while Ni exhibited uniformly extreme contamination (Class 6) with values between 8.53 and 11.51 exceeding WHO, (1996) limits throughout the study area

Contamination Factor (CF)

Contamination factors for soil samples were calculated based on the background values of heavy metals in the crust. The results revealed significant variability across the study area. Cadmium showed extreme variability, from 0.02 to 14.7, with very high contamination observed in the Al Fayoum and Itsa Districts, recording values of 7.8 and 9.5, respectively. In contrast, Tamyah, Sanories, and Ibshway Districts (north of the study area), exhibited low to moderate contamination levels with average values of 1.72, 0.87 and 2.75, respectively. Nickel demonstrated significant pollution in most soil samples with the main class (considerable contamination) in all districts and a value equivalent to 5, except in Al Fayoum district (Fig. 6).

Translocation factor (TF)

The translocation of heavy metals from roots to stems in wheat crops showed limited mobility, with values ranging from 0.09 to 1.14 for cadmium and from 0.04 to 1.62 for nickel (Fig. 7). Notably, 92% of sampling sites demonstrated values less than 1(Figs. 9, D4 and E4); this may be due to the plant's natural defense mechanisms that prevented the uptake of excess metals or to the limited mobility of Cd and Ni in the soil (Rawat er al., 2018). Meanwhile the highest translocation factors (greater than 1) for Cd and Ni were recorded only in three sites in Itsa District and at the border between Sanories and Itsa districts.

Bioaccumulation factor (BF)

The bioaccumulation factor revealed limited heavy metal uptake in wheat crops across samples and varied from 0.008 to 0.883 for Cd and up to 0.006 for Ni, these results indicate that Cd was more prevalent than Ni in this area, which showed that the wheat crop is less efficient in accumulating metals, indicating a lower risk of metal contamination in food crops (Radovanovic et al., 2020) (Fig. 8). According to Tudi *et al.*, (2021) low BF might be attribute to the age-dependent accumulation or defense or tolerance mechanisms of the plant to avoid toxic levels in physiological organs.

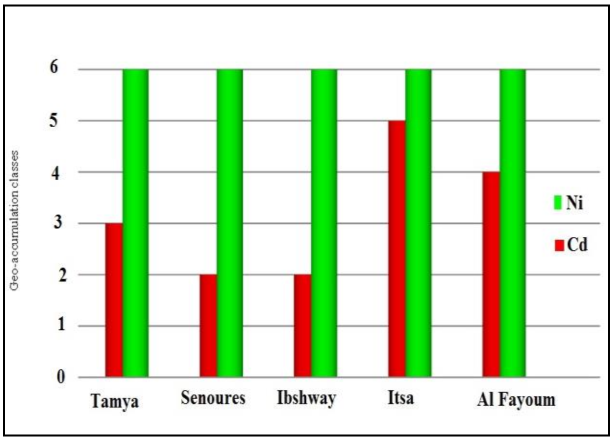

Fig. 5. I-geo index values order in the study area.

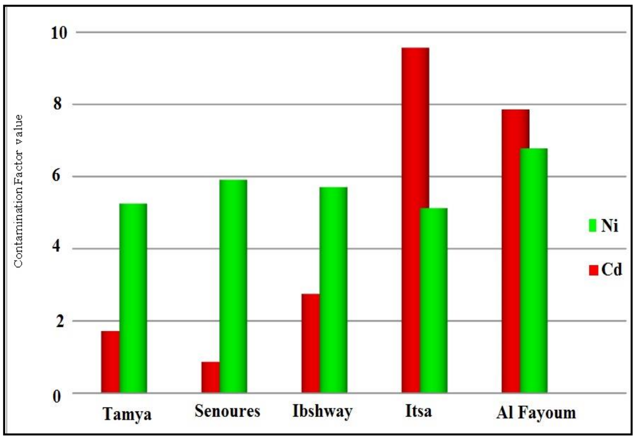

Fig. 6. Contamination Factors values in the study area.

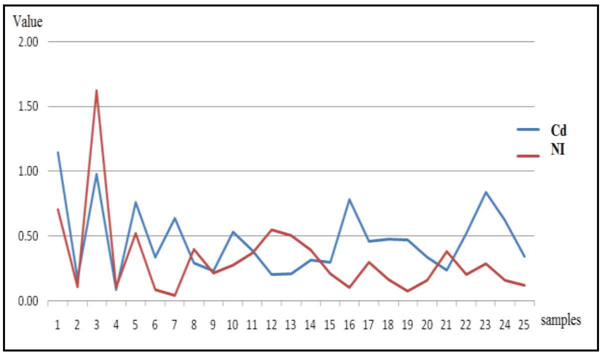

Fig. 7. The Translocation Factors values in the study area.

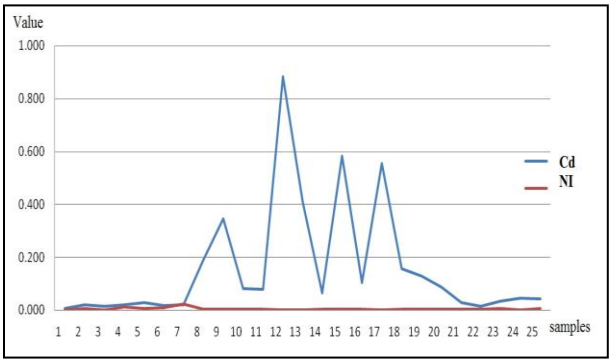

Fig. 8. Bioaccumulation Factors values in the study area.

Spatial Prediction of Soil potentiality

Both maps and the model (Fig. 3 and 9) were integrated alongside to identify the most relevant variables explaining the significant spatial variation of metal distribution. Figure.3, illustrates the output variables, including soil properties such as ECe, pH, $CaCo_3$ and organic matter, as well as the pollution indices, include The Geoaccumulation index and Contamination Factor. The other output variables, including topographic features like slope, elevation, and aspect, and finally soil productivity features like NDVI and land use, were clustered together in two subclusters. Adjacent to this subcluster, cadmium and nickel distributions were grouped as a single subcluster, indicating their distributions, and the interaction with other variables was studied.

This clustering highlights the strong relationship between different stability features in influencing heavy metal distribution. Selection of these indicators depended mainly upon available literature (Abdellatif *et al.*, 2021; Ahmed *et al.*, 2021; Saleh *et al.*, 2021).

Some variables were shown to be strongly correlated, as detailed in Table. 4, between cadmium, nickel and some soil characteristics as follows:

Positive correlations were observed between total Cd concentration and electrical conductivity (ECe) (r=0.109), pH (r=0.244**) and $CaCO_3$ (r=0.053).

On the other hand, negative correlations were found with organic matter (r=-0.184*).

For total Ni, negative correlations were identified with $CaCO_3$ (r=-0.244**).

These findings highlight the influence of soil properties on the spatial distribution of Cd and Ni. The positive correlation of Cd with ECe, pH $CaCO_3$ suggests that these factors enhance Cd accumulation, while organic matter a reduce its presence. For Ni, the negative correlations with CaCO3 indicate that it may limit Ni accumulation (**Chhabra, 2021**).

Table 4. Correlation coefficients between some soil characteristics and heavy metals.

	Cadmium	Nickel	ECe	pH	$CaCO_3$	O.M
Cadmium	1					
Nickel	0.656**	1				
ECe	0.109	0.074	1			
pH	0.244**	0.138	-0.067	1		
$CaCO_3$	0.053	-0.244**	0.046	0.053	1	
O.M	-.184-*	0.001	0.059	0.027	-.204-*	1

O.M Organic matter, ECe Electrical Conductivity, pH measure of the acidity or basicity, $CaCO_3$, Calcium carbonate
* correlation is significant at the 0.05 level and ** correlation is significant at the 0.01 level

The best methods for generating a prediction quality map of each cadmium and nickel were presented in (Fig. 3), by examining the soil properties stability map reveals that soil pH along with calcium carbonate have a significant effect on the model since they captured the highest amount of the total variance shared.

The spatial distribution of soil chemical factors salinity and calcium carbonate in Al Fayoum Governorate (Fig. 9/A-C) indicated that Al Fayoum soils suffer from soil salinity, which ranged between 1.03 dS/m and 10.3 dS/m. Accordingly, the slightly saline covered about 72.2% of the total area while moderately saline category was revealed in several sites, occupying 27.4% of the total cultivated area of Al Fayoum soils. The pH of Al Fayoum soils contained averages of 7.53 to 8.96; these data exhibited that the main category of soil pH of Al-Fayoum governorate is consider as Moderately alkaline, except for 15.8% throughout both Ibsheway and Itsa Districts, which recorded Strongly alkaline levels.

The calcium carbonate content in the soil ranges from 2.98 to 35.2, with medium and high soil calcium carbonate contents distributed at 75.2%, 51.4%, 83.2% and 29.4% in Tamia, Ibshaway, Itsa and Fayoum districts, respectively.

The soil properties stability map categorizes the soils into four groups with two main soil groups; the first one, medium risk, includes 40 samples and covers 34% of the studied areas, while the second is larger with 85 soil samples and 65.2% and defined as low risk. What is interesting is the absence of no-risk soils throughout the study area.

The generated pollution indices quality map for cadmium highlights the entity of high risk soils in the southwestern part of the study area with an area enclosing 38% of the total area, while medium risk soils are located in the eastern and western northern parts of study area and cover 40% of the total area. The very stable soils generally distributed in the middle parts.

The significant effect of the geo-accumulation index, and Contamination Factor on the distribution of stability indices was clearly seen.

In contrast, the nickel pollution indices stability map shows an inverse pattern, with 69% of the total area classified as medium risk, with the effect of the sequence order: Contamination Factor, Translocation Factor, Geo-accumulation Index, and Bioaccumulation Factor.

The soil physical quality map categorizes the soils into four groups; low risk and medium risk covered 79% of the total area. These findings highlight the influence of soil topography on the spatial distribution, especially for digital elevation model DEM and slope which have a significant effect on the model.

Based on (**Figure. 9 and 10**) and (**Table 1**), it was observed that soil chemical parameters and heavy metal distribution contributed the most to the overlaying maps, which were the best predicting variables with 60%, side by side with pollution indices, topographic and productivity features.

(**Fig. 10/H**) depicts the map obtained after overlaying and summing up the results of the IDW method with soil classification according to **FAO, (2006**). The spatial map identified soil classes for heavy metals, which were divided into 4 categories. For cadmium, the north and middle area, which possess about 42.4% of the total area considered no/low risk while southern parts which suffering from high concentrations of cadmium distribution and other pollution indices enclose 47.1% and 10.4% of the total area as medium/high risk, respectively.

On the other hand, Nickel potentiality map supports the previous distribution of heavy metal concentration and soil properties results, with the absence of no-risk soils throughout the study area with the major soil class being medium risk with an area about 72.8% of the total area distributed among the study areas except in some several sites in eastern and western parts considered high risk and cover 3.8%, and low risk areas found only in Itsa and Tamyah districts.

These results underscore the spatial variability of Cd and Ni contamination, with soil properties, heavy metal distribution, pollution indices, topographic and productivity features playing critical roles in determining potential risk levels.

As shown in (**Fig. 6)**, the overall soil quality ranged from low risk (high quality) to high risk (low quality). Results in (**Table 5**) show that high qualities soils for both Cadmium and Nickel covered nearly 42.4% and 23.3% of the total area, respectively, and were found mainly in the northern district for cadmium and in Itsa and Tamya districts for Nickel. These soils had none to slight physicochemical limitations, which in turn increased the overall soil quality. The moderate quality soils occupied 47.1% for Cadmium and occurred mainly in southern parts and72.8% for Nickel of the total area, and occurred mainly in all study area except a scattered patch in tItsa and Tamya districts . Soils of very low and low qualities covered about 1.04% and 3.8% of the total area for cadmium and nickel, respectively, and occurred mainly in the northern parts besides a scattered patch in the southwestern parts.

Integrating the layers of CQ indicators, resulting in Table 5, shows that the soils had a low to medium quality. As shown, soils of preferred high qualities (a low risk) represented nearly 65% of the total area in all parts except the edges of the western parts which covered about 34% of the total area,with he moderate quality soils in scattered patches . Hence, applying leaching fraction, and adding of organic and mineral amendments (gypsum) are the most recommended practices (**Abdelaal *et al.*, 2021**).

Table 5. The % value and area by feddans/thousands of different stability feature.FAO,(2006).

		soil properties	soil topographic	soil productivity	Cd pollution indices	Ni pollution indices	Cd potentiality	Ni potentiality
No Risk	Fadden	0.442	32.7	261.4	0	0	0.442	0
	%	0.1	7.4	59.1***	0	0	0.1	0
Low Risk	Fadden	288.4	156.6	0.0	37.6	21.6	187.6	103.0
	%	65.2	35.4	0.0	8.5	4.9	42.4	23.3
Medium Risk	Fadden	153.0	192.0	158.4	215.4	307.5	208.4	322.1
	%	34.6	43.4	35.8**	48.7	69.5	47.1	72.8
High Risk	Fadden	0.442	61.0	22.5	189.8	113.2	46.0	16.8
	%	0.1	13.8	5.1*	42.9	25.6	10.4	3.8

***no productivity, ** medium productivity, *** high productivity**

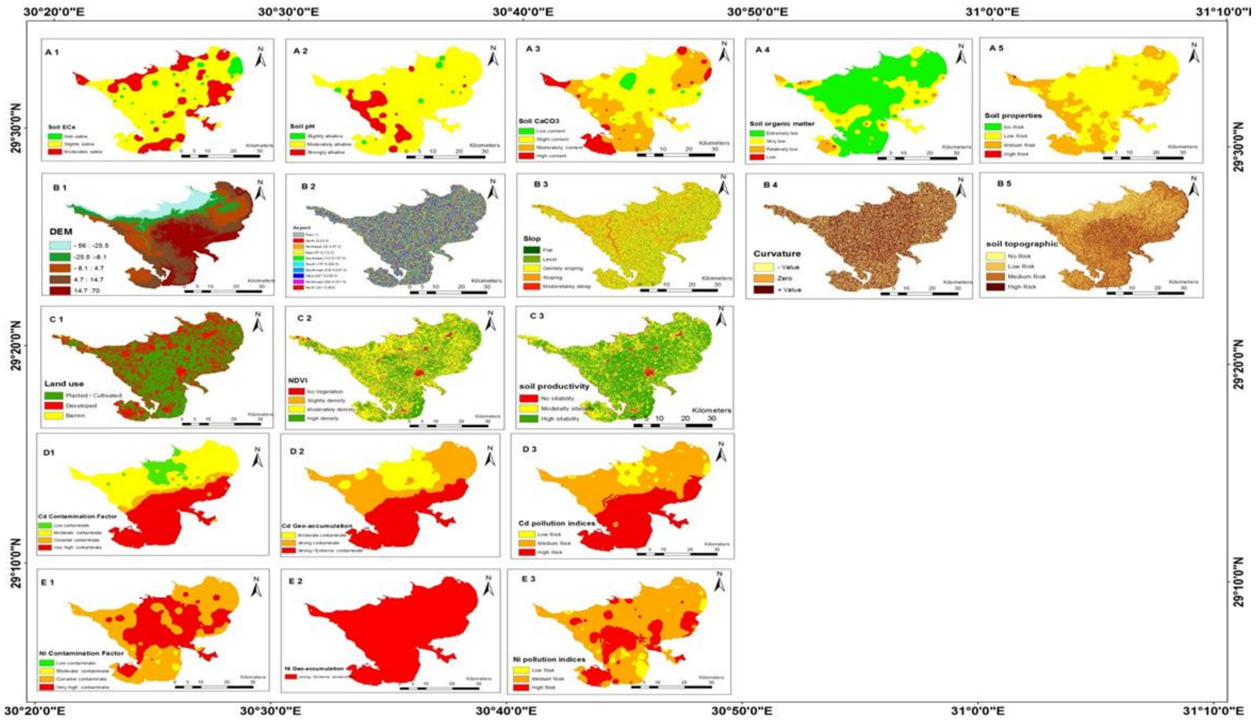

Fig. 9. (A.1) Soil Ece, (A.2) Soil pH, (A.3) Soil CaCO3, (A.4) Soil organic matter, (A.5) Soil Properites overlay, (B.1) DEM, (B.2) Soil Aspect, (B.3) Soil slop, (B.4) Soil Curviture, (B.5) Soil Topographic overlay, (C.1) Soil Landuse, (C.2) NDVi, (C.3) Soil Productivity overlay, (D.1) Soil Cadmium Contamination Factor , (D.1) Soil Cadmium Geo-accumulation index, (D.2) Soil Cadmium Bioaccumulation Factor , (D.3) Cadmium Pollution indices overlay, (E.1) Soil Nickel Contamination Factor, (E.2) Soil Nickel Geo-accumulation index and (E.3) Soil Nickel Pollution indices overlay.

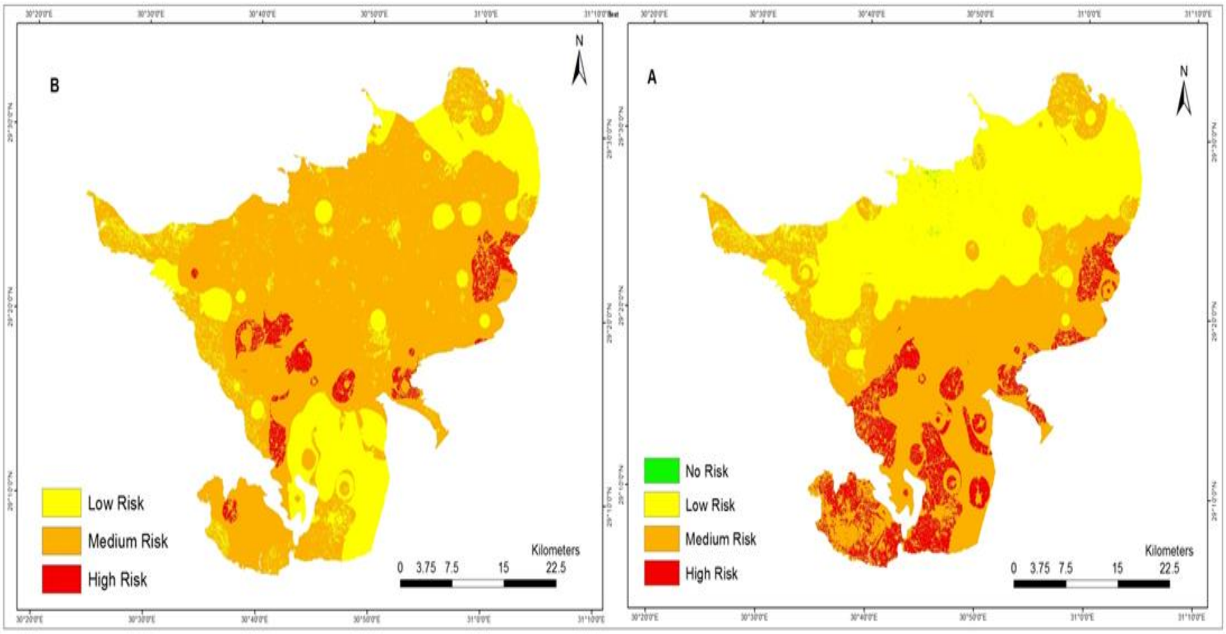

Fig. 10. Soil Cadmium potentiality map and (B) Soil Nickel potentiality map.

Discussions

Based on WHO (1996) international standards, the critical limit of soil properties and heavy metals in soil was set at 0.8 mg/kg^{-1} and 35 mg/kg^{-1} for cadmium and nickel, respectively. As described in the classification guidelines (FAO, 2006), heavy metals contamination is classified into four categories: uncontaminated, light contaminated, contaminated and high contaminated. Significant variations were observed in the values of these two metals (Table 3). Therefore, spatial distribution was conducted to assess the levels of heavy metals in the various soil types studied in Al Fayoum Governorate (Fig 4).

The spatial distribution of soil salinity and calcium carbonate in Al Fayoum Governorate (Fig. 9A-9C) indicated that the saline soils adjacent to Qaroun Lake and in the southern parts of Itsa and Al Fayoum districts, are attributed to factors such as parent material, poor drainage, and a shallow water table (less than 80 cm) due to seepage from the lake's saline water (Ahmed, 2021). These leads directly to reduced growth characteristics, yield components (Alshaimaa, 2022).

The calcium carbonate content in the soil ranges from 2.98 to 35.2, with medium and high soil calcium carbonate contents distributed at 75.2%, 51.4%, 83.2% and 29.4% in Tamia, Ibshaway, Itsa and Al Fayoum districts, respectively. This is especially evident within the study area, where the main component is calcareous soil with higher amounts of calcium carbonate, which affects soil properties and heavy metal behavior (Abd El-Aziz et al., 2025).

The distribution of heavy metals (Fig. 3A), showed that the soil samples studied in the southern part of Al Fayoum Governorate, including Al Fayoum and Itsa districts had contaminated and high contaminated levels of cadmium, particularly near factories (illegal irrigation from canals and drains). This may be due to industrial wastewater containing cadmium at high levels or due to the high soil pH values of 7.9 and the application of phosphate fertilizers. However, these values show a decrease in quantity compared to the results of Ahmed, (2019) and Abdurrahman, (2012); this decrease in levels may be due to the regulated use of fertilizers and the controlled use of mixed water. Meanwhile (Fig. 3B), it was shown that the total Ni concentration of Al Fayoum Governorate was not considered polluted in only 35% of the total area across the districts of Tamyah, Ibsheway and Itsa due to the calcareous soil origin and distance from Lake Qaroun. The highest concentration of Ni was found in the northern and central parts of Al Fayoum Governorate (Senouries and Ibsheway districts), resulting from the poor quality of illegal irrigation water from canals and drains that reach Lake Qaroun (Ahmed, 2019). Meanwhile, higher Ni concentrations were recorded in the central region of Al Fayoum Governorate, which includes several areas connected to the districts of Seniors, Ibsheway, Itsa and Al Fayoum; these results may be attributed to lower $CaCO_3$ content and higher pH values (Abd El-Aziz *et al.*, 2025).

Based on the results of this study and the geospatial distribution of heavy metals in soil, it is clear that the central and southern regions of Al Fayoum Governorate participate in the amount of contamination of soil heavy metals (contaminated and high contaminated) for total Cd and Ni metals; these results align with the distribution of both metals observed by Abdurrahman (2020), Ahmed, (2019), and Abd El-Aziz *et al*, (2025) but disagree with the concentration values, which showed a noticeable improvement.

On the other hand, results of the pollution indices revealed that I-geo index values followed the following order: Ni > Cd, due to exceeding WHO (1996) limits. This order corresponds to the absolute concentration and distribution of metals, confirming widespread anthropogenic pollution in more than 85% of the studied soils, particularly in the southern regions (Itsa and Al Fayoum districts). Meanwhile, the values of the contamination factor followed the following order: Cd > Ni, showing a very high contamination category as a major class in both Itsa and Al Fayoum districts; this is thought to result from human activity, fertilizer application, and elevated levels of pH and $CaCO_3$ (Rashid, 2010).

The transport factor results from 25 plant samples showed that wheat did not experience any significant metal translocation from roots to stems, compared to Nawaz *et al.*, (2021), who calculated the maximum accumulation of cadmium and nickel in wheat at 1.82 and 1.99 mg/kg^{-1}. However, based on the results, the transport factors for these metals in plants were significantly lower than the threshold of 1 (non-accumulating) and safe for cultivation in most of Al Fayoum Governorate. Based on these results, wheat is considered an excluder of cadmium, showing no significant accumulation or adverse effects on the plant. This result is consistent with the bioaccumulation factor values for the heavy metals, cadmium and nickel, which ranged from 0-0.016 to 0.003-0.883, respectively, further confirming that wheat does not accumulate heavy metals from contaminated soil. These results collectively demonstrate that wheat acts as a non-accumulator or excluder of heavy metals like Cd and Ni, making it a suitable crop for cultivation in areas with moderate heavy metal contamination (e.g., Yang *et al.,* 2014).

Integrating the layers of CQ indicators which included several factors such as salinity, pH, $CaCO_3$, and OM, which properties that play an important role in plant growth, and thus they constrain soil function (Blume *et al.*, 2016). Result in Table.5 showing that the soils had a low to medium quality. As shown, soils of preferred high qualities (low risk) represented nearly 65% of the total area in all parts except the edges of western parts which covered about 34% of the total area, with the moderate-quality soils in scattered patches. Hence, addition of organic and mineral amendments is the most recommended practices (Abdelaal e*t al.*, 2021)

The PQ with main limiting factors were DEM, slope, aspect and curvature varing from Grade I to Grade V (Table 5), which showed that very high and high-quality soils occupied 7% and 35% of the total area, respectively (Fig. 9, B5). The remaining area was dominated by medium and low quality soils (43% and 13%) in the central and southern areas. these variations may be attributed to elevation and slopse which reflect on depth of groundwater, low water retention and quality of drained canals. Therefore, enhance the soil physical quality by using of tillage operations in additions to the application of fertilizers is essential (Abdelaal *et al.*, 2021)

Results in Table 5 show that the ranges of SQs varied from high quality (low risk) to low quality (high risk) with absence of very high quality (no risk) for both metals. these ranges indicated that quality grades were classified for Cd and Ni respectively, as follow: high quality (low risk), occupied 42.4% covering the northern area for Cd and 23.3% occupied some scattered patchs in northeastern and southern parts for Ni, medium quality representing 47.1% which focused in the central southern parts for Cd, and 72.8% covering most area of Al Fayoum for Ni .On the other hand, low quality (high risk) covered area enclose 10% and 3% and occurred mainly in the southern parts for Cd besides a scattered patch in the eastern and western parts for Ni, respectively.

Finally, previous results line up with several United Nations Sustainable Development Goals (SDGs), especially SDG 3 (Good Health and Well-Being) by evaluating heavy metal risks to food safety, SDG 15 (Life on Land) through estimating soil contamination and developing sustainable land management.

Conclusions

This study confirmed the importance of monitoring and management strategies to address heavy metal pollution in agricultural soils in Al Fayoum Governorate, by examining the levels of two heavy metals, cadmium and nickel, in soils that relatively exceeded the critical limits in some district parts, with particular concern for cadmium and nickel due to their harmful effects on plants and potential entry into the food chain.

The IDW method could adequately produce thematic layers for several indicators, to generate four indices, i.e., CQ, PQ, PSQ , ISQ and the overall SQ. The studied soils had varied overall quality classes ranging from the very low to very high. Soils of favorable quality (low risk and medium risk) covered nearly 90% for cadmium and 95% for nickel of the total area.

The calculation of the geoaccumulation index indicated a significant accumulation of nickel in the soils; however, it is important to note that the study assessed both the enrichment factor and contamination factor to evaluate heavy metal pollution in the area. The results showed moderate pollution based on the enrichment factor but strong pollution based on the contamination factor, suggesting higher contamination levels compared to the background values.

Nevertheless, the results indicate that the different concentrations of cadmium and nickel in Al Fayoum soils, besides soil characteristics, have the largest influence on soil potential. Therefore, improved management is essential for monitoring heavy metal contamination. The aggregate potential prediction map for the study area was effective in identifying potentially degraded areas, which should be developed.

These findings underscore the importance of monitoring and management strategies to address heavy metal pollution in agricultural soils by integrating soil chemical, physical, fertility and environmental aspects, which is necessary when assessing Soil Quality to achieve sustainable agricultural development.

Declarations

Ethics approval and consent to participate

Consent for publication: The article contains no such material that may be unlawful, defamatory, or which would, if published, in any way whatsoever, violate the terms and conditions as laid down in the agreement. **Availability of data and material:** Not applicable

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