Assessment of Heavy Metal and Physical-chemical Contamination in Roadside Soils along Duhok to Zakho highway, Kurdistan Region, Iraq

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Received: 04 /06/2025 *Accepted: 04 /07 /2025* *Published: 01 /09 /2025*

Abstract:

Soil plays a vital role in food production, making sustainable soil management essential for environmental and agricultural health. This study assesses heavy metal contamination and physico-chemical properties of roadside soils along the Duhok to Zakho highway in the Kurdistan Region, Iraq. Increased vehicular traffic on public roads has notably affected soil quality. Understanding the impact of highways on soil properties is critical for achieving sustainability. In this investigation, 20 soil samples were collected from both the left and right sides of the highway at distances of 5 m and 15 m from the road edge, at a soil depth of 0–15 cm. The samples were analyzed for physical properties (soil texture, moisture content, organic matter, field capacity) and chemical properties (pH, electrical conductivity, organic carbon, nitrogen, C:N ratio), along with concentrations of the heavy metal lead (Pb). The analysis showed that soil texture varied among sites—classified as clay, sandy clay loam, loam, or sandy loam—indicating general suitability for arable crops. Results revealed pH ranged from 4.40 to 6.60, EC from 0.72 to 1.02 dS/m, organic matter from 0.13% to 6.12%, nitrogen from 0.08% to 0.84%, moisture content from 2.90% to 15.00%, field capacity from 27.51% to 37.93%, and organic carbon from 0.29% to 3.68%. Lead concentrations ranged from 2.00 to 3.11 mg/kg and exceeded WHO permissible limits. Farmers are encouraged to use soil health cards and apply sustainable management practices.

Keywords: Heavy metal contamination; Physical-chemical properties; Roadside soils; Soil pollution; Vehicular emissions.

INTRODUCTION

Roadside soils are critical components of the environment and are frequently polluted by vehicle emissions, road maintenance, and other anthropogenic activities. Heavy metals and organic pollutants are particularly concerning, as they are persistent in the environment and pose significant risks to both ecosystem and human health (Alloway, 2012).

Highways such as the Duhok to Zakho road in the Kurdistan Region of Iraq are increasingly prone to pollution due to rising traffic volumes and nearby industrial activities (Al-Khashman, 2004). Rapid infrastructure development in urban and semi-urban areas like the Kurdistan Region further raises the risk of physico-chemical contamination of roadside soils (Lindgren, 1996).

Heavy metals including Pb, Cd, Zn, and Cu are non-biodegradable and persistent in soils. They can enter the food chain by transferring from soil to plants (Kabata-Pendias, 2000; Khalil & Hassan, 2024), and their toxic and bioaccumulative properties may pose long-term ecological and health hazards (Alloway, 2012). Numerous studies have shown that concentrations of these pollutants are highest near roadways and decrease with distance (Kabir et al., 2022).

The mobility and bioavailability of heavy metals are influenced by soil's physical and chemical properties such as pH, organic matter, and cation exchange capacity (Men et al., 2018; Hassan & Umer, 2022). These factors affect soil fertility and its ability to support plant growth. Therefore, examining both heavy metal concentrations and key soil parameters is essential to evaluate environmental risks (Li et al., 2016).

Contaminants in roadside soils disrupt soil ecosystem functions, reduce fertility, and pose health risks via food chain transfer. These risks are amplified by changes in soil pH, electrical conductivity (EC), and organic matter content (Chen et al., 2010). The persistence of pollutants like lead, which can still be detected in soils years after the ban of leaded gasoline, demonstrates their long-term environmental stability (Facchinelli et al., 2001).

Accurate assessment of potentially toxic elements (PTEs) in roadside soils is crucial for informing soil remediation efforts and environmental policymaking, especially in fast-growing regions such as the Kurdistan Region of Iraq (Wei & Yang, 2010). Although global interest in roadside contamination has grown steadily over the past four decades, newly industrializing nations remain underrepresented in the literature. Iraq and the Kurdistan Region, in particular, have experienced limited research due to ongoing conflicts, political instability, and resource constraints.

One notable site of potential concern is the Duhok-Zakho highway corridor in the Duhok Governorate. Despite its ecological and economic significance, this region has received minimal scientific attention regarding environmental monitoring. For nearly 40 years, studies have focused on roadside pollution globally, yet research in Iraq remains scarce.

The scale of vehicular activity in the region is substantial. The number of registered vehicles in Duhok Governorate rose from 128,205 in 2011 to 270,315 in 2023 (Najmaldin & Sagvan, 2024). In 2022 alone, the Ministry of Planning's Transportation and Communication Department recorded 120,143 newly registered vehicles, of which 102,690 were passenger cars and 17,453 were cargo vehicles. Duhok Governorate contributes 13.5 km of main roads and 44.95 km of sub and rural roads to the region's paved network, which totals 53.468 km of main roads and 92.229 km of sub and rural roads. This intensive traffic and infrastructure contribute heavily to soil pollution, especially with hazardous heavy metals.

The Kurdistan Region, and Duhok in particular, faces serious challenges stemming from the rapid rise in vehicle numbers and unregulated industrial development. This study fills a critical research gap by evaluating the levels of heavy metal contamination and physico-chemical properties of roadside soils along the Duhok-Zakho route, offering one of the first comprehensive assessments of its kind in this region. The findings aim to support future environmental monitoring, risk assessment, and sustainable land management in Iraq.

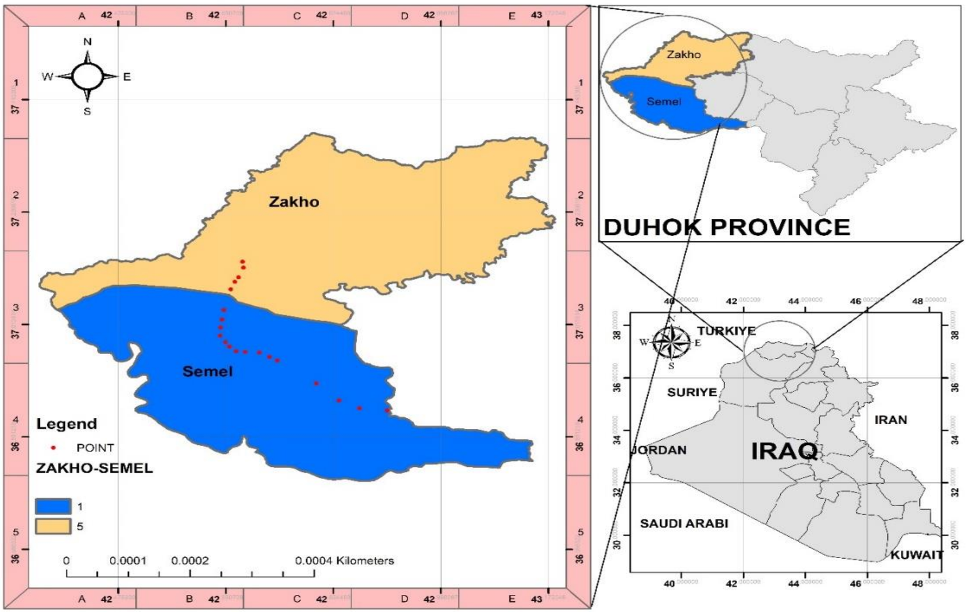
2. MATERIALS AND METHODS

2.1 Study Area

The study was conducted at 20 roadside sites along the national highway connecting Duhok and Zakho in the Duhok province, part of the Kurdistan Region of Iraq. This highway, which spans approximately 50 kilometers, serves as a primary route between the two cities. The surrounding area is predominantly agricultural, and the road accommodates a wide variety of vehicles, including small, medium, and large vehicles running on either gasoline or diesel. The highway was selected for this study due to its status as the busiest road in the Duhok province, with thousands of vehicles traveling daily.

The region has a semi-arid to Mediterranean climate, with hot, dry summers and cold, wet winters. Average annual rainfall ranges between 400 and 700 mm, mostly falling between November and March. Temperatures can exceed 40°C in summer and drop below freezing in winter.

According to previous studies and soil classification maps, the dominant soil types in the area include clay loam and silty clay soils, with calcareous characteristics and moderate drainage capacity. These soils are suitable for agriculture but sensitive to contamination due to their fine texture and binding properties.



A map showing the sampling locations along the highway is presented in Figure 1.

2.2 Sample Collection

Soil samples were collected in September 2023. A total of 20 sites were selected along both sides of the highway, with sampling intervals of 2 to 3 kilometers. The collection alternated between the right and left sides of the road. At each site, one soil sample was taken at distances of 5 to 15 meters from the road edge. The samples were randomly distributed around the observation point and collected using a stainless-steel ditch auger. Each sample was taken at a depth of 0-15 cm and within a surface circumference of 15-30 cm. The sampling sites were chosen to represent areas with varying land use patterns, including proximity to industrial areas, agricultural fields, and residential zones. The collected samples were stored in labeled polyethylene bags, transported to the laboratory, and air-dried at room temperature before undergoing chemical analysis.

2.3 Sample preparation and analysis

In the laboratory, soil samples were air-dried at room temperature, crushed, and sieved through a 2 mm mesh to remove debris and ensure uniform particle size. The prepared samples were stored in airtight containers for further analysis. The soil sample for Metal analysis was digested using concentrated Nitric acid. A 0.5 g sample was digested in a Teflon vessel, heated, and diluted with deionized water to a final volume of 50 ml. The concentrations of heavy metals (Pb) were measured using an Atomic Absorption Spectrophotometer. Soil pH and Electrical Conductivity (EC) was measured in a 1:2.5 soil-to-water suspension using a calibrated pH meter and EC meter, respectively. Organic Matter Content was determined by the Walkley-Black method. Soil Texture was analyzed using the hydrometer method to determine sand, silt, and clay fractions.

2.4 Statistical Analysis

Statistical analysis was performed using GraphPad Prism (Version 10.2). Descriptive statistics, including mean, standard deviation, and coefficient of variation, correlation Matrix, were calculated.

3. RESULTS and DISCUSSION

Soil texture class among the 20 sites varied, with loam being the most frequent textural class in 13 sites (Table 1). It has been discovered that soils with loam consist of the ideal sand, silt, and clay ratios, which help in better water retention and aeration (Weil & Brady, 2017). Sandy clay loam and sandy loam textures prevailed in sites with higher sand content (e.g., Sites 2, 13, and 15). Sandy soils are generally characterized by less water-holding capacity but better drainage, which can impact plant growth and nutrition (Gee & Or, 2002). Site 12 and 19 comprised clayey texture with 59.75% and 47.55% clay content, respectively. Clay soils have good water-holding capacity but inferior drainage and aeration, which can restrict root development (Shukla, 2023), also leading to an increase in pollutant accumulation due to reduced mobility (Men et al., 2018).

Organic content was also not consistent across the sites, ranging from a low of 0.13% (Site 12) to a high of 6.12% (Site 3). Higher organic matter was found in loams, namely for sites 3 (6.12%), 5 (5.21%), and 17 (5.77%), and this can increase soil fertility because of enhanced nutrient retention as well as microbial activity (Lal, 2004). The OM is crucial for soil fertility and plays a role in the adsorption of heavy metals, affecting their mobility and bioavailability (Li et al., 2016). Conversely, sandy soils at Sites 2 (1.34%) and 13 (0.62%) generally had lower concentration of organic matter due to rapid rates of decomposition and lower storage potential of organic matter (Schmidt et al., 2011). Lower OM concentration at Site 12 (0.13%) may be attributed to the high clay content of high clay content, which impacts decomposition rates and stabilization of organic matter (Six et al., 2002). The very low levels of organic matter at Sites 12 and 19 suggest poor soil health attributed to either prolonged vehicle pollutants or detrimental environmental factors.

Soil water content ranged from 2.90% (Site 20) to 15.00% (Site 2). In general, sandy loam soils (e.g., Site 2: 15.00%) contained higher soil water content, which may be attributed to a greater rate of infiltration and storage of water in lower horizons (Rawls et al., 2003). Low soil water content in clayey soils (e.g., Site 19: 7.70%) suggest lower infiltration rate, which will lead to surface collection of water and potential runoff (Dexter et al., 2011).

Site capacity ranged between 27.51% (Site 19) and 37.93% (Site 14), of which loamy soils registered maximum values. A higher field capacity in loam soils shows its ability to store water for vegetation growth and offers good aeration and drainage (Lal, 2019) and is also crucial for microbial processes (Chen et al., 2010). For sandy loam locations such as Site 2 (35.17%) and Site 15 (34.90%), potential agriculture under proper control of irrigation management (Shukla, 2023). These findings suggest that a clear understanding of local soil-water relationships is essential to guide land use planning and sustainable agricultural practices.

The variation in soil texture, organic matter, and water retention among the experimental locations highlights the need for site-specific soil management. Loamy soils, possessing a proper balance of physical properties, may be farmed with a mix of crops, while sandy soils may be amended with organic materials to enhance the water-retention capacity (Lal, 2004). Clayey soils may be improved by facilitating drainage to prevent waterlogging and compaction (Dexter et al., 2011). The research emphasizes the need for soil characterization to optimize land use and agricultural productivity.

Table 1: Soil Texture and Properties Across Different Sites

Site	Sand (%)	Silt (%)	Clay (%)	Textural Class	Organic Matter (OM) (%)	Soil Moisture (%)	Field Capacity (%)
1	46.90	24.40	28.70	Sandy Clay Loam	3.13	8.20	32.43
2	69.11	18.79	12.10	Sandy Loam	1.34	15.00	35.17
3	45.30	31.00	23.70	Loam	6.12	13.50	35.69
4	34.51	44.43	21.06	Loam	4.34	10.00	35.10
5	42.83	36.34	20.83	Loam	5.21	9.00	33.25
6	36.41	40.49	23.10	Loam	4.45	5.00	37.60
7	40.91	38.03	21.06	Loam	4.65	11.00	37.79
8	49.83	33.31	16.86	Loam	5.54	7.00	36.81
9	32.74	47.58	19.68	Loam	5.02	7.70	32.82
10	49.87	35.76	14.37	Loam	5.52	7.20	34.98
11	37.77	39.65	22.58	Loam	4.78	8.60	33.23
12	11.27	26.98	59.75	Clay	0.13	10.75	35.89
13	54.80	13.94	31.26	Sandy Clay Loam	0.62	8.35	33.63
14	49.61	26.90	23.49	Loam	5.31	7.75	37.93
15	59.60	27.88	12.52	Sandy Loam	3.47	8.10	34.90
16	52.24	25.86	21.90	Sandy Clay Loam	3.35	12.10	37.73
17	43.50	33.43	23.07	Loam	5.77	11.30	35.32
18	47.56	35.12	17.32	Loam	5.46	6.10	31.43
19	39.58	12.87	47.55	Clay	0.17	7.70	27.51
20	39.93	37.65	22.42	Loam	4.66	2.90	29.80

The correlation matrix (Table 2) reveals the existence of significant relationships among soil texture fractions (sand, silt, clay), organic matter (OM), soil moisture content, and field capacity. These reflect interactions among soil properties and how together they can affect soil behavior, fertility, and water-holding capacity.

Sand and clay content were strongly negatively correlated (r=−0.67), with soils with greater sand content also having lower clay content and vice versa. This inverse relationship is well-documented in soil science literature, as sand and clay occupy opposite ends of the soil texture continuum (Gee & Or, 2002). Similarly, silt content was negatively correlated with sand (r=−0.41) and clay (r=−0.40) content, suggesting that as one fraction increases, the other decreases due to natural particle-size distribution (Weil & Brady, 2017).

Organic matter (OM) was positively and strongly correlated with silt content (r=0.73), indicating that soils with higher silt content have higher organic matter content. This can be explained by the fact that silt particles can provide a habitat for the buildup of organic matter and microbial activity (Schmidt et al., 2011). In contrast, a strong negative correlation was observed between OM and clay (r = −0.66), likely due to reduced aeration and slower decomposition rates in clay-dominant soils in clayey soils (Six et al., 2002). Weak positive correlation between OM and sand (r=0.06) demonstrates that sandy soils hold less organic matter, in accordance with their low nutrient-retention capacity (Rawls et al., 2003).

Soil moisture content was poorly correlated with soil texture fractions, with a moderate positive correlation with sand (r=0.19) and an almost neutral correlation with clay (r=0.02). The poor correlation could indicate that soil moisture is influenced more by other parameters such as organic matter content, land use, and environmental conditions rather than texture alone (Lal, 2019). Soil moisture was, however, inversely correlated with silt (r=−0.28), suggesting that soils with higher silt content can have slightly inferior moisture retention, perhaps due to structural effects on water movement (Shukla, 2023).

Field capacity, or the ability of the soil to retain water following excessive drainage, was moderately positively related to soil moisture (r=0.40), which signifies that soils containing higher moisture content also retain more water at field capacity (Rawls et al., 2003). Organic matter also had a positive correlation with field capacity (r=0.27), indicating the higher the content of organic matter, the greater the water retention due to its hydrophilic nature and possibility of structure improvement in the soil (Dexter et al., 2011).

The findings of the correlation matrix point to the function of organic matter in soil property improvement, particularly in water retention capacity (Lal, 2004). Loamy soils with more silt and moderate organic content would typically be good in moisture retention and fertility and are therefore cultivable. On the other hand, poorer organic sandy soils may require amendment with compost or biochar to improve water-holding capacity and nutritional content (Schmidt et al., 2011). The lack of correlation between soil texture and water content illustrates the requirement for site-specific irrigation management, particularly in arid or semi-arid environments (Men et al., 2018).

Table 2: Correlation Matrix of Soil Physical and Chemical Properties

Variable	Sand%	Silt%	Clay%	OM%	Soil Moisture%	Field Capacity%
Sand%	1.000	-0.41	-0.67	0.06	0.19	0.09
Silt%	-0.41	1.000	-0.40	0.73	-0.28	0.18
Clay%	-0.67	-0.40	1.000	-0.66	0.02	-0.25
Organic Matter (OM%)	0.06	0.73	-0.66	1.000	-0.20	0.27
Soil Moisture%	0.19	-0.28	0.02	-0.20	1.000	0.40
Field Capacity%	0.09	0.18	-0.25	0.27	0.40	1.000

In addition to texture-related interactions, examining key chemical properties such as organic carbon, total nitrogen, and electrical conductivity provides further insights into soil fertility and pollutant behavior. The content of soil organic carbon (OC) also varied widely across the sites, ranging from 0.29 g/kg at Site 12 to 3.68 g/kg at Site 3. OC was greatest at Sites 3, 5, 6, 7, 8, 11, 14, 17, and 18, all of which exceeded 2.5 g/kg, suggesting the incidence of higher inputs of organic matter, perhaps due to plant residues or microbial activity (Lal, 2004). On the other hand, Sites 12, 13, and 19 had very low OC contents ($<$ 0.50 g/kg), which indicated weak accumulation of organic matter, possibly due to environmental factors such as erosion or lack of dense vegetation cover (Schmidt et al., 2011).

Total nitrogen (TN) content followed a similar pattern, with concentrations ranging from 0.08 g/kg at Site 12 to 0.84 g/kg at Site 3. The strong association between OC and TN contents implies that organic matter is mostly accountable for nitrogen storage in the soils, as abundantly illustrated by soil fertility research (Six et al., 2002). Sites with higher TN content ($>$ 0.5 g/kg) also contained higher OC, corroborating the role of organic matter in nitrogen cycling and storage (Weil & Brady, 2017).

The C/N ratio, which reflects organic matter decomposition rates and nitrogen availability, varied mostly from 4:1 to 7:1 across sites. Most sites had a ratio of 5:1, which indicates relatively stable decomposition and nutrient cycling (Lal, 2019). However, Site 7 had the broadest C/N ratio (7:1), suggesting slower organic matter decomposition and potential nitrogen immobilization (Weil, 2000). Broader C/N ratios, such as at Sites 1, 2, 12, and 15 (4:1), indicate higher nitrogen mineralization rates, which can enhance plants' nutrient availability (Paul, 2014).

Electrical conductivity (EC) ranged from 0.72 dS/m at Site 20 to 1.02 dS/m at Site 6, indicating small differences in soil salinity. EC values were less than 2.0 dS/m at all sites, indicating non-saline conditions that are conducive to plant growth (Shukla, 2023). Site 6 recorded the highest EC, which may be due to localized mineral deposition or irrigation activity that leads to greater salt concentrations in soil (Richards, 1954).

Table 3 illustrates that soil pH ranged from 4.4 to 6.6, which is slightly acidic to acidic. The lowest pH was recorded at Sites 12 and 19 (pH = 4.4), while Site 3 had the highest pH (6.6). The variation in pH could be regulated by decomposition of organic matter, soil parent material, and anthropogenic activities such as pollution or agricultural input (Lal, 2004). Soils at Sites 12 and 19, can promote the solubility of heavy metals, thereby raising their bioavailability and environmental hazards (Al-Khashman, 2004). Soils with higher content of organic matter (e.g., Site 3) had somewhat higher pH values, which was likely due to buffering from organic compounds (Schmidt et al., 2011).

Because acidic conditions can increase heavy metal solubility, especially lead, it is important to assess Pb distribution across the sites. Concentrations of Lead (Pb) ranged between 2.00 mg/kg (Site 7) and 3.11 mg/kg (Site 11) with significant site variation. Highest concentrations of lead were recorded at Sites 10 (3.00 mg/kg) and 11 (3.11 mg/kg), possibly due to their proximity to roads and vehicular emissions (Alloway, 2013). Lead contamination in soils is normally due to traffic-related sources, industrialization, and atmospheric deposition (Wuana & Okieimen, 2011). Concentrations were especially high at locations near to industrial areas and regions of heavy traffic, highlighting the combined influence of vehicular emissions and road surface degradation (Kabir et al., 2022). As shown in Table 3, correlation analysis revealed significant associations between Pb and components of soil texture, indicating that finer soils (clay and silt fractions) have higher Pb concentrations. This is in agreement with the findings of Facchinelli et al. (2001), who indicated that clay particles offer a larger surface area for metal adsorption, resulting in the retention of more contaminants.

Soils with higher organic carbon content in the soil, such as Site 3 (OC = 3.68 g/kg, Pb = 2.92 mg/kg), tended to have moderate lead levels, indicating the potential role of organic matter in the retention and stabilization of lead (Violante et al., 2010). In contrast, lower organic carbon locations, such as Site 12 (OC = 0.29 g/kg, Pb = 2.90 mg/kg), still contained relatively high Pb content, suggesting possible external pollution sources rather than soil organic matter interactions (Zhao et al., 2015).

The findings suggest that organic matter is a significant constituent of nitrogen retention, water retention, and metal stabilization in soils. Soils that have low OC and TN content, such as Site 12, may be amended with organic matter to increase soil fertility. The moderate EC and slightly acidic pH indicate that the soils are suitable for plant growth but may require occasional checks, particularly in the more acidic pH (< 5.0) regions to prevent nutrient imbalances. Lead pollution, though relatively low, suggests the need for continuous monitoring, especially in areas with high traffic exposure (Wuana & Okieimen, 2011).

Table 3: Soil Organic Carbon (OC), Total Nitrogen (TN), C/N Ratio, Electrical Conductivity (EC), pH, and Lead Concentration Across Sites

Site	OC (g/kg)	TN (g/kg)	C/N Ratio	EC (dS/m)	pH	Lead
1	1.67	0.40	4:1	0.76	5.9	2.32
2	0.76	0.21	4:1	0.84	4.8	2.65
3	3.68	0.84	4:1	0.89	6.6	2.92
4	2.79	0.62	5:1	0.81	5.7	2.72
5	3.02	0.66	5:1	0.85	6.2	2.78
6	2.85	0.58	5:1	1.02	5.8	2.11
7	2.91	0.42	7:1	0.97	5.9	2.0
8	2.88	0.61	5:1	0.90	6.1	2.77
9	2.60	0.54	5:1	0.86	6.0	2.88
10	2.49	0.51	5:1	0.83	5.9	3.0
11	2.84	0.53	5:1	0.84	5.7	3.11
12	0.29	0.08	4:1	0.85	4.4	2.90
13	0.41	0.09	5:1	0.79	4.8	2.40
14	2.76	0.60	5:1	0.84	6.1	2.88
15	1.83	0.41	4:1	0.87	5.5	2.8
16	1.79	0.46	4:1	0.83	5.4	2.42
17	2.94	0.58	5:1	0.81	6.4	2.12
18	2.85	0.62	5:1	0.86	6.2	2.31
19	0.49	0.09	5:1	0.77	4.4	2.4
20	2.93	0.50	6:1	0.72	5.3	2.30

Soil texture analysis indicated immense variability in sand, silt, and clay content among the study sites. Sand content ranged from 11.27% to 69.11%, averaging 44.21%, and possessed a coefficient of variation (CV) of 26.52%. Silt content ranged from 12.87% to 47.58%, averaging 31.52%, while clay content possessed the highest variability (CV = 46.75%), ranging from 12.10% to 59.75%. These findings reflect significant heterogeneity of soil texture, which can influence water holding capacity, nutrient delivery, and root development (Weil & Brady, 2017). Variations observed agree with previous literature recognizing the impact of soil texture on permeability and susceptibility to erosion (Shukla, 2023).

Organic matter (OM) ranged from 0.13% to 6.12%, and the mean value was 3.95% with a high CV of 48.57%. Similarly, organic carbon (OC) content varied from 0.29 g/kg to 3.68 g/kg and averaged 2.24 g/kg with a CV of 45.22%. This indicating a high spatial heterogeneity between sites, which may be associated with differences in land use, traffic density, and proximity to point sources of pollution. Such high variability in OM and OC reflects differences in vegetation cover, land use, and microbial activity (Lal, 2004). High organic matter content enhances soil fertility and water retention, resulting in enhanced agricultural productivity (Lehmann & Kleber, 2015).

Soil water content ranged from 2.90% to 15.00%, with an average of 8.86% and a CV of 32.19%. Field capacity, a critical water status parameter, exhibited relatively low variability (CV = 8.01%) and ranged between 27.51% and 37.93%, averaging 34.45%. The values indicate moderate to high water-holding capacity, which is required for plant growth in semi-arid conditions (Hudson, 1994). Soil moisture content variability is explained by land cover, topography, and rainfall distribution variation (Rawls et al., 2003).

Soil pH ranged from 4.40 to 6.60 with a mean of 5.66 and a CV of 11.18%. These are near-neutral to slightly acidic conditions that influence nutrient availability and microbial processes (Kirkby, 2001). Electrical conductivity (EC) was relatively uniform (CV = 8.00%) and ranged from 0.72 to 1.02 mS/cm, which represents low to moderate levels of salinity that are within tolerable ranges for most crops (Richards, 1954).

Total nitrogen (TN) was 0.08 g/kg to 0.84 g/kg with a mean of 0.47 g/kg and CV of 44.14%. Spatial differences in nitrogen application by variation in organic matter content and fertilizer application are difficult to explain and could be responsible for the wide range (Stevenson & Cole, 1999). Plants need suitable nitrogen levels for growth and yield that may be limited by nitrogen deficiency, especially where organic matter is low in sandy soils (Schlesinger, 1997).

Lead (Pb) concentrations ranged from 2.00 mg/kg to 3.11 mg/kg with an average of 2.59 mg/kg and a CV of 12.78%. The concentrations are within the expected range for unpolluted soils (Pendias, 1992). Considering the study sites' proximity to road networks, and as previously discussed, vehicular and industrial sources appear to influence Pb concentrations, further supported by spatial variations (Alloway, 2012). Monitoring needs to be regular to assess potential risks to human health and crop production.

These patterns emphasize the need to actually consider prior physical and chemical properties in environmental forward searches of heavy metals and related pollutants. The occurrence of acidic soils, elevated Pb levels, and low organic matter in specific locations indicates possible ecological hazards and necessitates thorough monitoring and customized mitigation approaches. These results are further interpreted with the aid of figures, as shown below, which provide a comprehensive understanding of the study's environmental implications.

Table 4: Descriptive Statistics for Soil Properties

Property	Min	Max	Mean	Std. Error	Variance	SD	Geometric Mean	Coeff. Var (%)
Sand (%)	11.27	69.11	44.21	2.62	137.47	11.72	42.13	26.52
Silt (%)	12.87	47.58	31.52	2.10	87.86	9.37	29.92	29.74
Clay (%)	12.10	59.75	24.17	2.53	127.66	11.30	22.35	46.75
Organic Matter (OM, %)	0.13	6.12	3.95	0.43	3.68	1.92	2.83	48.57
Soil Moisture (%)	2.90	15.00	8.86	0.64	8.14	2.85	8.37	32.19
Field Capacity (%)	27.51	37.93	34.45	0.62	7.60	2.76	34.34	8.01
Organic Carbon (OC, g/kg)	0.29	3.68	2.24	0.23	1.03	1.01	1.85	45.22
Total Nitrogen (TN, g/kg)	0.08	0.84	0.47	0.046	0.043	0.206	0.39	44.14
pH	4.40	6.60	5.66	0.14	0.04	0.63	5.62	11.18
Electrical Conductivity (EC, mS/cm)	0.72	1.02	0.85	0.015	0.005	0.068	0.84	8.00
Lead (Pb, mg/kg)	2.00	3.11	2.59	0.074	0.11	0.33	2.57	12.78

Figure 1 illustrates correlations among field capacity, soil moisture, organic matter, and soil texture. Loam soils with greater field capacity and organic matter levels were noted, supporting observations by Shukla (2023) that loamy soils support growth as a result of adequate aeration and moisture levels. The strong correlation between organic matter and field capacity ($R^2 = 0.72$) shows the contribution of OM in enhancing water-holding capacity (Lal, 2019).

Figure 1 demonstrates that changes to these parameters underscore the complicated relationship between soil makeup and its capacity to hold moisture and nutrients. Loamy soils with a higher content of organic matter showed an increased field capacity, reflecting their capability to hold water for extended durations—an essential factor for sustaining microbial activity and vegetation. In contrast, sandy soils, which prevail in certain areas, exhibited a lower field capacity owing to their coarse texture and diminished water retention capabilities. This resulted in quicker drainage and reduced moisture levels. In loam soils, the effect of organic matter on moisture retention is especially clear; as organic carbon increases, soil structure improves, leading to greater water-holding capacity and enhanced fertility (Li et al., 2016). The pattern observed in Figure 1 further confirms OM's role in enhancing field capacity through improved soil aggregation, reduced compaction, and better aeration, factors that ultimately influence the soil's capacity to sustain plant growth and reduce pollutant buildup.

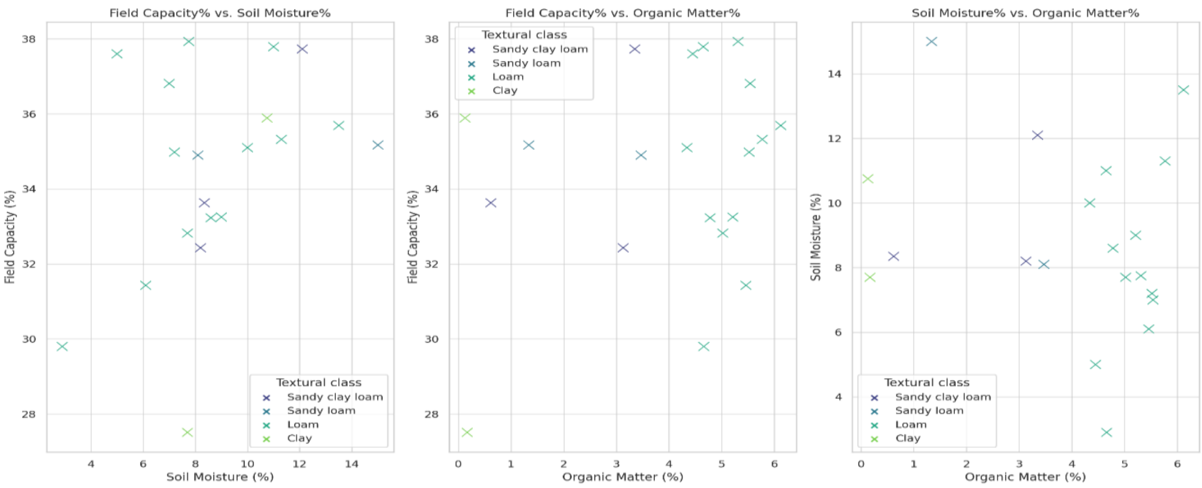


Figure 1: Relationships Between Field Capacity, Soil Moisture, Organic Matter, and Textural Classes of Soil

Figure 2 visually reinforces earlier observations by showing that loamy and clay soils exhibit higher field capacities than sandy loam. This aligns with research indicating that fine-textured soils retain more water due to high surface area and capillary forces (Weil & Brady, 2017), whereas coarse-textured soils drain rapidly due to larger pore spaces (Shukla, 2023).

Variability in FC within the same soil category reflects differences in bulk density, organic matter, and hardness (Rawls et al., 2003). Sandy loam exhibits minimal variation, indicating uniformity, while clay shows greater variability due to differences in mineralogy and organic matter content (Saxton & Rawls, 2006).

The right-hand side of Figure 2 highlights substantial variations in organic matter (OM) across soil textures. Loam soils contain the highest OM, followed by sandy clay loam, sandy loam, and clay. Loamy soils provide optimal conditions for OM accumulation due to moderate aeration and water retention (Lal, 2004). Clay soils, with reduced aeration, suppress microbial activity, limiting OM breakdown (Six et al., 2002), while sandy soils exhibit poor OM retention and high degradation rates (Oades, 1988).

Figure 2 also demonstrates the relationship between FC and OM, reinforcing that finer soils retain more moisture and organic matter. The lower FC in sandy loam and sandy clay loam suggests a higher risk of pollutant leaching, posing potential groundwater contamination hazards (Men et al., 2018). These findings align with studies showing that soil texture influences water retention and pollutant transport, affecting environmental sustainability (Facchinelli et al., 2001). Maintaining sufficient OM is crucial to reducing pollutant mobility and enhancing soil resilience, offering key insights into the environmental dynamics of roadside soils.

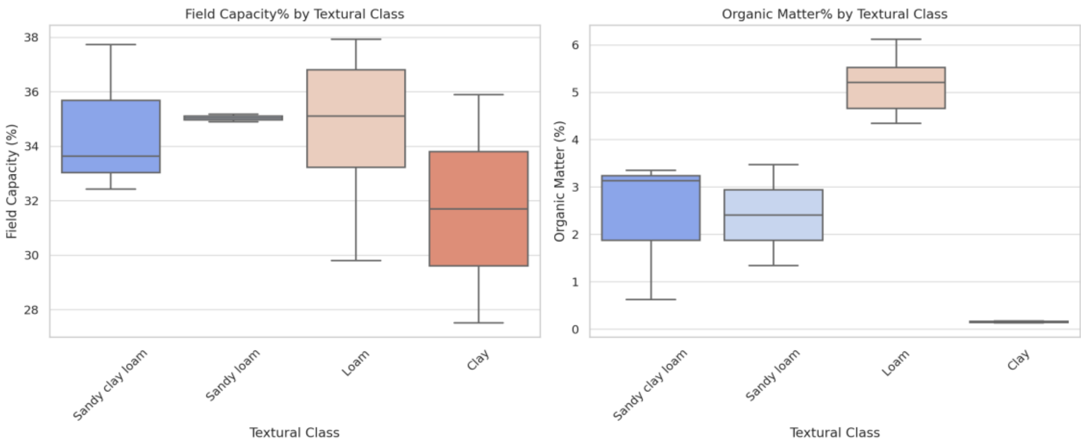


Figure 2: Field Capacity and Organic Matter Across Different Soil Textural Classes

Conclusion:

The rapid rate of urban and semi-urban development, similar to the Kurdistan Region, has increased the possibility of roadside soil contamination by physicochemical properties and heavy metals. The current study assessed soil properties on the Duhok-Zakho road, and it was discovered that there were significant variations in texture, organic material, moisture retention, and content of heavy metals. Loamy soils, which were predominant, were well-aerated and nutrient-retaining, whereas sandy soils were low in moisture retention and clayey soils exhibited drainage limitations. pH values differed at different points, influencing availability of nutrients and mobility of metals, while electrical conductivity (EC) indicated changes in soil salinity. Levels of total nitrogen (TN) were low and hence may imply nutrient deficiency. Lead (Pb) values were within tolerance but were noticeably greater near roads and industrial areas, indicating road and industrial emission inputs to the contamination.

The study identifies the need for site-specific management of soil for enhancing fertility as well as reducing pollution risks. Loamy soil is ideal for cultivation, whereas organic manuring is required in sandy soils, and improved drainage is required for clayey soils. Additionally, high levels of heavy metals by the roadside necessitate control methods to ensure healthy soil. Ultimately, this research advocates for soil characterization to enable effective land management. Future studies should conduct long-term soil monitoring to observe environmental dynamics and aid in sustainable land-use planning, particularly in rapidly developing regions.

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