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Analyzing Soil Physical Properties in Kirkuk City, Iraq, Utilizing a Geographic Information System – Based Inverse Distance-Weighted Technique

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ABSTRACT

In this research, the distribution and physical characteristics of soils are the main topics. The inverse distance weighting (IDW) method was used in conjunction with GIS to forecast the physical properties of the soil. This study involved a detailed analysis of 65 soil samples collected across Kirkuk City to investigate its physical properties and behavior. Through the creation of 10 digital maps using the IDW technique, the distribution of soil types, such as gravel, sand, silt, clay, dry density, specific gravity, Atterberg limits, and water content were illustrated. Variations in these properties were observed across different sectors of the city, with specific districts showing notable differences. The gravel content was particularly high in certain northeastern zones, while sand was the predominant soil type overall, and the silt content exhibited significant variability. Clay content, which is concentrated in the eastern and southern regions, has implications for agriculture and contamination control. A direct correlation between the clay content and Atterberg limits was observed, with the liquid and plastic limits (LL and PL) increasing with clay content. Additionally, dry density was highest in the northwestern region, and the water content generally remained high except in specific areas. The specific gravity values exhibited consistency across most regions. These findings offer valuable insights for geotechnical and engineering practices in Kirkuk City and are supported by a cross-validation technique that assesses the relationships between basic and studied physical attributes. The coefficient of determination, R squared (R^2), for the IDW maps indicated varying degrees of model fit to the data, with lower root mean square error (RMSE) values suggesting improved prediction accuracy. Overall, the study revealed strong correlations ranging from good to excellent across the examined regions. The use of GIS techniques has demonstrated significant effectiveness in modeling and quantifying soil properties, offering benefits in protecting and improving soil health through effective soil management strategies and treatments.

Keywords: soil, physical properties, inverse distance weighting, GIS.

INTRODUCTION

The impact of human activity on the Earth's surface is substantial, affecting resources vital for various physical needs, such as soil, flora, water distribution, urban areas, and settlements, as well as other physical features generated by human actions (Shareef et al., 2020). Soil, which plays a crucial role in these processes, is defined differently depending on the perspective. Farmers perceive soil as the decomposed area supporting plant and agricultural growth, while geologists view it as residual material from parent rocks facilitating root development. Engineers consider soil to be composed of earthly components atop the rock crust, encompassing liquids, gases, and mineral particles (Taqi et al., 2016).

This variation in soil definition reflects the complex interplay of physical, chemical, and biological processes that contribute to the significant geographic diversity of soils (Reza et al., 2010). Understanding the qualities and variability of soil is essential for developing effective agricultural policies, managing soils sustainably, and monitoring the environmental impact of land use (Chagas et al., 2016). Inadequate knowledge in this area could lead to the implementation of insufficient laws and regulations, potentially contributing to environmental degradation and increased carbon dioxide emissions (Chagas et al., 2016). Precise and comprehensive geographical soil data are crucial for sustainable land management, environmental modelling, risk assessment, and ecosystem restoration (Forkuor et al., 2017). The soil conditions in dry rangelands, for example, significantly influence the type, quantity, and quality of flora, underscoring the importance of soil property measurement and mapping in natural ecosystems (Hosseini et al., 2014). The physical and chemical features of soil, such as water retention, cation exchange capacity, fertility, internal drainage, and sorption characteristics, are believed to be strongly influenced by soil texture (Liao et al., 2013). Therefore, examining the physical, chemical, and geographic distribution of soil is vital for understanding its behavior across various land covers (Bellinaso et al., 2021). Geographical approaches, including the use of advanced technologies, such as geographic information systems (GIS) and modelling methods, are necessary to monitor the temporal and spatial variability in soil parameters (Salahalden et al., 2023). These methods provide continuous data that are challenging to obtain through traditional on-site procedures, making them critical for managing agricultural, ecological, and environmental resources effectively. The development of GIS and modeling methods has revolutionized the anticipation of soil qualities across landscapes, enabling the creation of high-resolution soil maps that surpass the capabilities of conventional survey methods (Salahaldenet al., 2024). These technological advancements are increasingly essential for modern soil resource management and environmental stewardship (Raheem and Omar, 2021). This study utilized the GIS techniques to map the soil zones in Kirkuk city, demonstrating the effectiveness of GIS in gathering, displaying, and analyzing topographically referenced data (Raheem and Omar, 2021) (Ahmed et al., 2022). Spatial interpolation techniques, particularly inverse distance weighting (IDW), are commonly used when soil sample data are unavailable, allowing for the estimation of soil parameters across regions (Li and Heap, 2011) (Sulyman et al., 2020). These techniques streamline the process by forecasting soil attributes based on known samples, reducing the need for extensive outdoor soil sampling and laboratory work (Pande et al., 2022).

The primary objective of this study was to create a distribution map of the physical properties of surface soil in Kirkuk utilizing the IDW method within the GIS program. Cross-validation techniques are employed to assess the relationship between basic and studied physical properties, providing insights into the effectiveness of the IDW method in this context. This study aimed to contribute to the understanding of soil characteristics and their spatial variability in Kirkuk, supporting informed decision-making in land management and environmental planning.

STUDY AREA AND WORK METHODOLOGY

Location and geography of the study area

Kirkuk, the capital of the Kirkuk Governorate in Iraq, boasts a rich cultural heritage and a diverse population, making it one of the ancient governorates of Iraq (Najat et al., 2014) (Najatet al., 2016). Renowned for its history and significant oil reserves, Kirkuk stands out as an oil-rich region with some of the world's best-quality oils (Najat et al., 2014). The city's geographical coordinates are defined by the Universal Transverse Mercator System (UTMS) reference orientation project scheme zone 38 N, covering approximately 9.680 square kilometers, which represents approximately 2.2% of Iraq's total area (Najat et al., 2020). Situated at an elevation of approximately 350 m above sea level, Kirkuk lies at 35° 28' 5" N and 44° 23' 31" E (Najat et al., 2020), as depicted in Figure 1. Geographically, Kirkuk features a varied terrain characterized by elevated areas in the northern half, extending approximately 786 kilometers from the Arabian Gulf, contrasted with flat expanses elsewhere (Omar et al., 2014). It is bordered by the Sirwan (Diyala) River to the southeast, the Hamrin Mountains to the south, the Zagros Mountains to the northeast, and the Zap and Tigris Rivers to the west (Omar et al., 2014). These geographical features contribute to Kirkuk's distinct landscape and environmental diversity.

Data sampling

In October 2023, a comprehensive survey was conducted across all areas of Kirkuk as an initial step to select locations for soil sampling and installation. Subsequently, soil samples were

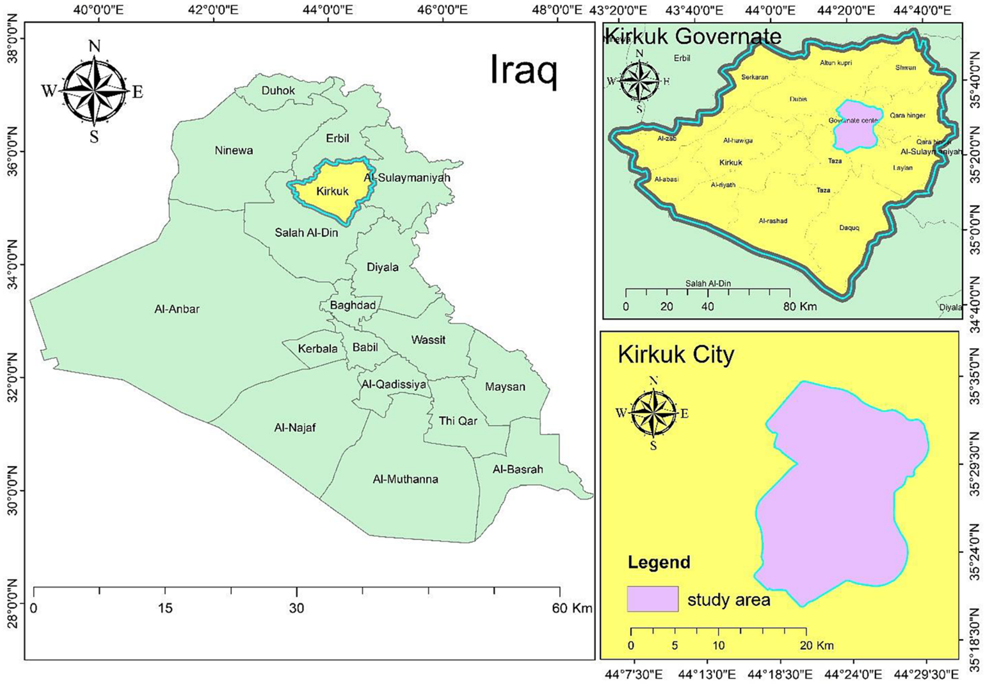

Figure 1. Map of the study area in Kirkuk, Iraq

extracted by digging the surface to a depth of 20–30 cm, with each sample collected from a distance of 2 km and carefully labelled before being placed in designated bags. A total of 65 samples were collected during this phase. The coordinates of these samples were precisely recorded using a GPS device, ensuring accurate spatial data collection across Kirkuk city's various districts, as depicted in Figure 2.

Following the fieldwork, laboratory analyses commenced to assess the physical properties of the collected soil samples. These analyses included measuring dry density and water content directly from the field using an HS-5001EZ

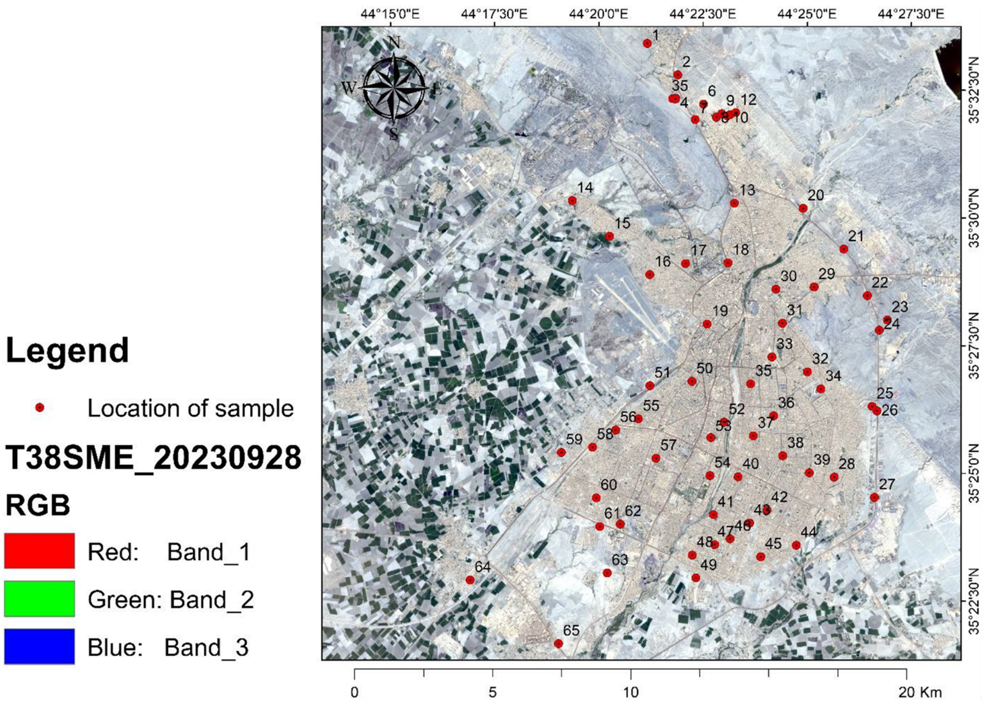

Figure 2. Surface soil sampling locations in Kirkuk City

moisture-density meter. Additionally, Atterberg limits, specific gravity, sieve analysis tests, and hydrometer tests were conducted according to the ASTM standards to determine the percentages of gravel, sand, silt, and clay within the samples. This meticulous approach ensured a thorough understanding of the soil composition and characteristics across the surveyed areas of Kirkuk.

Methodology

Assembling geographic data is often considered the most expensive and time-consuming aspect of creating a database for GIS applications (Chica-Olmo et al., 2019). This process involves two main categories of procedures: information integration and assembly. Information integration focuses on translating data while preserving its integrity, while data collection involves adding new data to a GIS (Chica-Olmo et al., 2019). The primary data source utilized in this study was the Kirkuk Construction Laboratory at TCK University, where the materials were tested. Additionally, field observations were collected for site investigations, and the physical properties of the soil were recorded for 65 distinct samples at various depths. The data collected during fieldwork included coordinates, moisture content, and dry density information for each sample point, measured using an HS-5001EZ moisture density meter. These data, along with the coordinates for each investigation site and laboratory data, were compiled into an Excel spreadsheet. Subsequently, utilizing tools within ArcMap, either a shapefile or a thematic map was generated.

The interpolation method used in this study, as depicted in Figure 3, was the IDW method. This technique was employed to interpolate the surface based on the collected points, enabling the construction of interpolation maps to visualize and analyze the spatial distribution of soil properties across the study area.

Interpolation techniques

Spatial interpolation refers to the calculation of unknown attribute values at unsampled locations using the measurements obtained from nearby sampled points, making it a crucial instrument for estimating continuous spatial data (Tan and Xu, 2014). Unlike conventional statistics, which rely on the random distribution theory of processes and variables, geostatistical analysis avoids many corresponding faults and restrictions, offering more robust and accurate results (Tan and Xu, 2014). Interpolation plays a vital role in GIS operations, because it is used to create many of the maps essential for local analysis (Setianto and Triandini, 2015). Consequently, spatial interpolation methods (SIMs) have become crucial for estimating biophysical variables in unsampled regions (Li and Heap, 2014). One of the most commonly used interpolation techniques is the IDW method, which involves estimating values at unsampled locations based on the distances and values of neighboring sampled points. This method assumes that the values closer to a particular location have more influence on the estimated value at that location, reflecting a gradual decrease in influence with increasing distance (Li and Heap, 2014). Through spatial interpolation methods, such as IDW, GIS applications can generate detailed and informative maps that aid in understanding the spatial patterns and distributions of various attributes (Setianto and Triandini, 2015).

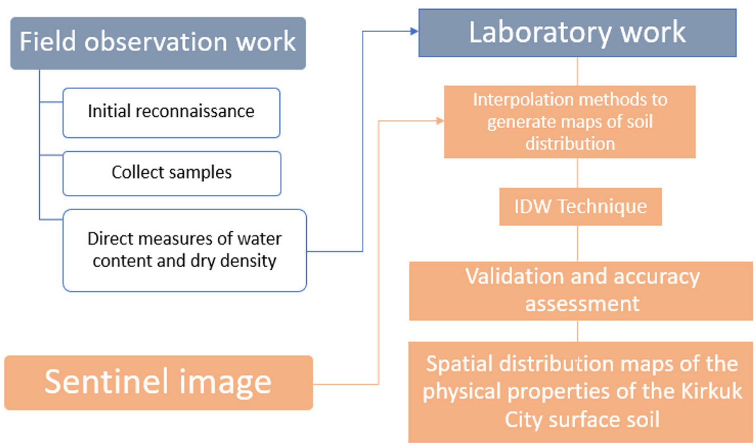

Figure 3. Flow chart of the applied method

Inverse distance weighting

All interpolation techniques are based on the principle that the points closer together exhibit stronger correlations and similarities than the points farther apart (Almasi et al., 2014). Among these methods, the IDW technique is one of the most significant and comprehensive approaches for interpolation (Yang et al., 2020) (Merza et al., 2023). In IDW, the surrounding points are organized in a linear sequence that is normalized by the inverse relationship between the distances of the tested and investigated locations (Yang et al., 2020) (Merza et al., 2023). This method relies on the concept that the distance between neighbors determines the similarity and correlation of their values, illustrating this relationship through a reverse distance function between each point and its neighbors (Almasi et al., 2014). Through the mathematical framework of the IDW method, GIS applications can effectively estimate attribute values at unsampled locations based on the characteristics of nearby sampled points, providing a valuable tool for spatial analysis and mapping (Merza et al., 2023). Equation 1 illustrates how to identify the IDW methodology:

$$Y_{\circ} = \sum_{i=1}^{N} \frac{y_i \, d_1^{-n}}{d_1^{-n}} \tag{1}$$

where: Y_o – value estimate for variable z at point I; y_i – an example of a point value I; d_1 – the distance in Euclid between the observed sample point and the calculated point; N – a weight coefficient dependent on a distance; n – inverse distance weighing power (Raheem and Omar, 2021).

Physical properties

The physical attributes of soil encompass various qualities crucial for different professions, including texture, water content, specific gravity, dry density, and Atterberg limits (Veyan et al., 2018) (Goldsmith et al., 2001) (Yesiller et al., 2014) (Das, 2013) (Ajaj et al., 2018). These attributes play essential roles in understanding the behavior and characteristics of soil as well as influencing decisions in agriculture, construction, and environmental management.

The water content in soil is fundamental, because it determines the three primary phases of soil composition: moisture, air, and solids (Veyan et al., 2018). This moisture includes hygroscopic, capillary, and gravitational moisture, each contributing uniquely to soil dynamics and properties (Veyan et al., 2018). Dry density is influenced by soil texture and moisture content, which dictates the maximum density achievable during compaction with a constant energy input (Goldsmith et al., 2001). The ideal moisture level for a specific soil texture enables the maximum dry density to be reached (Goldsmith et al., 2001).

Specific gravity is defined as the ratio of a material's density to that of a standard reference substance, which is crucial in geotechnical engineering for understanding the mass of soil solids compared to that of gas-free distilled water (Yesiller et al., 2014) (Das, 2013). For clayey and silty soils, the specific gravity typically ranges from 2.6 to 2.9 (Das, 2013).

Atterberg limits, also known as consistency limits, are pivotal indicators of soil mechanical and hydrological behavior, guiding agronomic and engineering practices (Ajaj et al., 2018). These limits include the liquid limit, plastic limit, and plasticity index, which reflect the transition of soil from liquid to plastic, then to semisolid or solid-states based on moisture levels (Das, 2013) (Balasubramanian, 2017). The difference between the LL and PL determines the plasticity index (PI) (Polidori, 2007).

Furthermore, particle sizes play a significant role in soil classification, distinguishing gravel, sand, silt, and clay particles (Das, 2013). Hydrometer tests are commonly used to analyze soil particle sizes, aiding in soil classification and understanding soil physical properties (Das, 2013). These attributes collectively contribute to a comprehensive understanding of soil characteristics, facilitating informed decision-making across various disciplines reliant on soil data.

RESULTS AND DISCUSSION

The results section presents a comprehensive overview of both field and laboratory findings related to soil properties. Field data include measurements of dry density and water content, capturing essential attributes directly from the sampled sites. On the other hand, laboratory experiments yield detailed physical property results, providing a deeper understanding of soil characteristics. Additionally, the spatial distribution of features, such as the library results, contributes valuable insights to the overall analysis. Table 1 serves as a reference point summarizing the measured physical characteristics of the soil across

Table 1. The physical properties of soil in Kirkuk

No	Place	Water content	Dry density	LL	PL	PI	Specific gravity	Gravel	Sand	Silt	Clay
1	Sekanyan 1	9.8	1.828	32.5	20	12.5	2.7	2	61.3	28.42	8.28
2	Sekanyan 2	5.8	1.575	30	19	11	2.77	16.3	42.6	35.28	5.82
3	Sekanyan 3	20	1.451	32	19	13	2.85	0	9.6	77.6	12.8
4	Sekanyan 4	5.2	1.755	28	18	10	2.85	0	0.3	91.51	8.19
5	Sekanyan 5	11.7	1.722	28.9	19	9.9	2.7	0.3	8.3	82.08	9.32
6	Shuraw 1	10.4	1.661	31	19	12	2.85	0.4	0.7	86.86	12.04
7	Shuraw 2	8.3	1.799	33.5	20	13.5	2.77	0.4	2.6	85.19	11.81
8	Shuraw 3	7.4	1.773	33	20	13	2.85	0	0.7	87.21	12.09
9	Shuraw 4	9	1.787	30.2	19	11.2	2.7	3	22.2	64.21	10.59
10	Shuraw 5	9.4	1.705	30	19	11	2.77	0.4	3.2	84.66	11.74
11	Shuraw 6	10.1	1.665	33	20	13	2.7	1	21	68.5	9.5
12	Shuraw 7	14.1	1.6	31	19	12	2.77	4	25.4	60.6	10
13	Rahimawa	9.7	1.704	42.7	23.8	18.9	2.85	0	0.14	95.61	4.52
14	Amal shabi 1	14.2	8.85	17	14.2	2.8	2.5	0.6	33	59.61	6.77
15	Amal shabi 2	12.9	1.74	23.4	15.6	7.8	2.5	0.5	10.42	83.54	5.56
16	Failaq	10.1	1.714	20.2	0	20.2	2.66	3.1	29	65.01	2.89
17	Arafa	12.9	1.61	24.1	14.4	9.7	2.66	1.4	30.28	58.67	9.67
18	Almas	14.7	1.446	27.93	16.1	11.83	2.66	10.9	16.82	63.14	9.16
19	Shara jumhurya	13.1	1.588	26.2	18.1	8.1	2.67	2.8	23.16	66.16	7.92
20	Sulaymania-Hawli road 1	10.3	2.14	24.8	19.8	5	2.85	24.7	38.12	34.86	2.32
21	Sulaymania-Hawli road 2	15.2	1.704	35	21.3	13.7	2.85	21.4	27.48	42.9	8.26
22	Sulaymania-Hawli road 3	11.3	1.892	22	18.9	3.1	2.85	20.1	33.6	41.61	4.73
23	Hawli road 1	12.8	1.818	34.2	20	14.2	2.77	0	0.3	86.57	13.13
24	Hawli road 2	18.8	1.8	28.5	19	9.5	2.857	0	0.1	88.72	11.18
25	Hawli-Panja ali road 1	5.3	1.852	27.5	18	9.5	2.85	0	17.56	70.77	11.67
26	Hawli-Panja ali road 2	12.5	1.7	43	22	21	2.85	2.4	2.3	56.33	38.97
27	Hay senaay-Panja ali 3	4.4	1.817	19.6	14.6	5	2.85	9.2	35.22	46.64	8.98
28	Panja ali 4	12.6	1.528	27.1	15.6	11.5	2.66	2	11.14	78	8.86
29	Darwaza	19.19	2.017	18.7	13.9	4.8	2.66	11.9	29.92	46.46	11.68
30	Azadi-Eskan	14.1	1.785	21.4	15	6.4	2.66	12.6	11.94	54.32	21.14
31	Shurja 1	14.6	1.802	35.25	29	6.25	2.6	5.9	12.34	76.62	5.1
32	Shurja 2	9.9	1.819	23	18.1	4.9	2.85	3.4	24.48	57.51	14.47
33	Qasab khana-Musala	16.5	1.875	28.2	15.6	12.6	2.6	0.1	24.64	60.1	15.12
34	Al-hwrya	19.5	1.501	36.3	23	13.3	2.85	3	6.26	76.1	14.64
35	Ronaki	12.1	1.667	27.15	17.5	9.65	2.66	5	16.46	68.98	9.56
36	Hiwa	12.4	1.571	23.3	14.3	9	2.86	1.8	13.52	71.05	13.67
37	Al-aroba	9	1.59	21.9	20.6	1.3	2.85	0.2	16.72	69.71	13.41
38	Hisabat	15	1.594	29.7	18.3	11.4	2.66	0.6	25.7	61.79	11.89
39	Al-qadsiya	7	1.972	24.5	14.9	9.6	2.66	0.3	28.6	61.07	10.07

40	Al-asra u mafqouden 1	9.9	1.72	31	19.6	11.4	2.67	0.9	7.2	71.64	20.3
41	Al-asra u mafqouden 2	6.5	1.898	24.7	15.3	9.4	2.66	1.5	14.16	74.07	10.27
42	Hay askari	10.3	1.635	22.4	17.5	4.9	2.66	0.4	23.42	63.49	12.67
43	Al-zoura 1	13.4	1.572	23.3	16.1	7.2	2.85	0.7	25.22	56.27	17.83
44	Al-zoura 2	5.7	1.797	32.65	16.9	15.75	2.66	0	2.94	87.16	9.9
45	Aso - Al-aofq	11	1.709	33.1	20.5	12.6	2.85	0.8	5.9	80.11	13.21
46	Al-shaab	13.1	1.649	28.5	19.4	9.1	2.66	0.3	13.46	76.56	9.64
47	Domiz	10.7	1.998	29.5	21.4	8.1	2.66	0.8	3.4	70.89	24.95
48	Hassar	8	1.754	26.8	14.1	12.7	2.66	0.6	12.36	76.46	10.6
49	Kubani	8.1	1.694	28	16.5	11.5	2.66	1.2	7.3	71.32	20.2
50	Tesain	16	1.73	25.7	17.3	8.4	2.73	0.8	14.74	69.13	15.29
51	Hamzali	15	1.98	39.8	22.1	17.7	2.85	1.8	10.54	64.84	22.82
52	Gernata	3.1	1.984	20.4	16.7	3.7	2.66	0.5	26.86	63.83	8.85
53	Al-mansour	3.1	1.779	21.9	20	1.9	2.85	3.2	38.9	45.09	12.77
54	Hay adan	4.9	1.797	24.6	17.6	7	2.8	0.2	16.28	71.71	11.83
55	Al-khazhra	12.7	1.731	24.2	18.1	6.1	2.84	14.1	14.86	59.59	11.47
56	Shoqq gaz shimal	18	1.588	20.8	17.3	3.5	2.66	8.9	12.32	64.52	14.28
57	Hay Wasti	7.5	2.031	36.2	18.9	17.3	2.66	1.2	4.14	69.98	24.64
58	Al-sekk	5.5	1.842	28.3	17	11.3	2.78	0.5	10.48	81.72	7.32
59	Hay badr	8.5	1.78	34	19.4	14.6	2.66	0.9	11.8	71.07	16.25
60	Wahid Huzayran	8.5	1.637	27.9	16.7	11.2	2.85	0.1	9.28	84.95	5.65
61	Madynati	18	1.544	31.5	19	12.5	2.66	0.7	3.24	82.44	13.6
62	Al-zouhor - TCK	12.3	1.442	24.3	13.1	11.2	2.66	1.2	5.18	87.74	5.84
63	Sayada	18	1.373	27.6	17.6	10	2.67	0.1	10.64	78.39	10.87
64	Hay senaay old	8.9	1.71	28	11.4	16.6	2.73	0.4	4.96	82.65	11.99
65	Hay senaay - jardagly	8	1.614	24.4	16.5	7.9	2.73	4.5	16.88	73.29	5.29

the investigated area and consolidating key information for further interpretation and discussion.

Field measurements

Field measurements were conducted to determine the water content and dry density of the soil. The water content ranged from 3.1% to 20%, with the AL-Mansour and Gernata regions having the lowest water content at 3.1%, while the Sekanyan region had the highest water content at 20%. In terms of dry density, the values ranged from 1.373 g/cm³ to 8.85 g/cm³. The Sayada region had the lowest dry density value of 1.373 g/cm³, while the Amal Shabi region had the highest dry density value of 8.85 g/cm³. These measurements provide crucial insights into the variations in water content and dry density across different regions within the investigated area.

Laboratory and statistical analysis

The Atterberg limits were crucial in delineating the sites where sediment transitions occurred between different physical states. The liquid limit ranged from 17% to 43%, with the Amal Sahbi region exhibiting the lowest percentage and the Hawli-Panja Ali Road exhibiting the highest percentage. In terms of the plastic limit, values ranged from 0% to 29%, with the Shurja region showing the highest percentage (29%) and the Failaq region displaying the lowest percentage (0%). The plasticity index, which measures the discrepancy between the liquid and plastic limits, ranged from 1.3% to 21%.

According to the particle size analysis, the gravel content was generally low across the 65 soil samples, varying from 0% to 24.7%. The Sulaymania-Hawli Road had the highest gravel percentage (24.7%), while most locations had negligible gravel content. The sand content ranged from 0.1% to 61.3%, with the Sekanyan region showing the highest percentage (61.3%) and Hawli Road showing the lowest percentage (0.1%). Silt predominated in many samples, ranging from 28.42% to 95.61%. The Rahimawa region had the highest silt percentage (95.61%), while the Sekanyan region had the lowest (28.42%). The clay content ranged from 2.32% to 38.9%, with Hawli-Panja Ali Road exhibiting the highest percentage (38.9%) and Sulaymania-Hawli Road the lowest (2.32%).

The specific gravity measurements fell between 2.5 and 2.857, with Hawli Road recording the highest value (2.857) and the Amal Shabi region the lowest (2.5). These detailed measurements provide valuable insights into the physical characteristics and composition of soil across different regions within the study area.

Spatial distribution-based IDW

The interpolation technique, known as inverse distance weighting, was used to forecast the distribution of soil attributes in Kirkuk city. On the basis of the information gathered from 65 sites, 10 soil properties – including gravel, sand, silt, clay, water content, dry density, specific gravity, liquid limit, plastic limit, and plasticity index – were examined. Seventy percent of the soil samples served as training data for the characteristics of the soil. It is necessary to validate the map that was derived from these data. To compute RMSE and ascertain the difference between the actual and projected values, 30% of the soil samples were utilized as testing data. Digital maps in GIS are created using IDW methods and a surface approximation algorithm based on soil parameters at known sites. The technique calculates critical soil parameters for missing locations using inverse distance evaluation, ensuring that all measured properties are comparable (Ibrahim et al., 2023).

Physical properties

Seventy percent of the soil samples were allocated as a training dataset to evaluate the spatial distribution of physical attributes, and the IDW method was used to generate corresponding maps (Veyan et al., 2018). These physical characteristics were categorized into five distinct regions—very low, low, medium, high, and very high – utilizing the IDW technique. A color scale was used to represent these areas, with green indicating lower proportions and bright purple representing higher proportions. The unique spatial distribution characteristics within Kirkuk city were explored in this study. The IDW analysis revealed, as depicted in Figure 4, that the northeastern part of Kirkuk city exhibited the highest percentage of gravel. The conducted investigation yielded lower results compared to the gravel content conducted for the soil of Kirkuk City in 2021 by (Raheem and Omar, 2021), which exhibited the highest percentage of gravel in

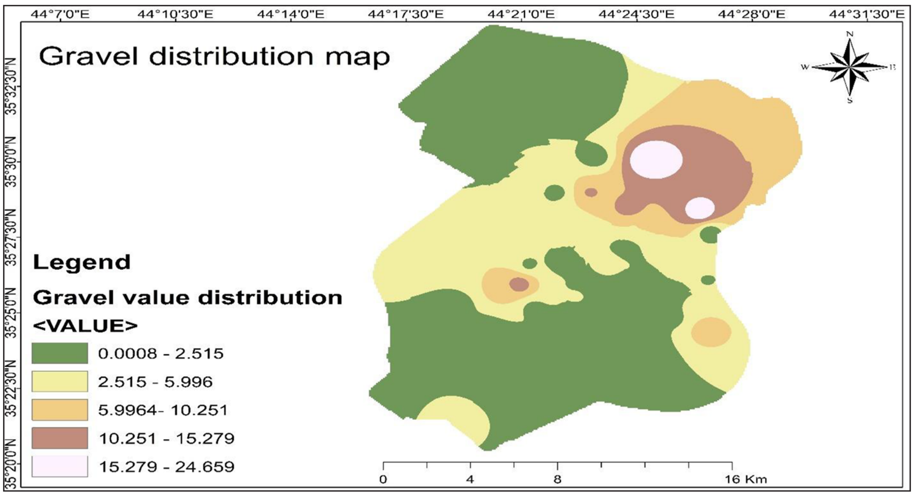

Figure 4. IDW representation of the gravel content value

the middle and western zones. Figure 5 illustrates that the northern region had the highest proportion of sand. The conducted investigation yielded similar results, but in different zones compared to the sand content conducted for the soil of Kirkuk City in 2021 by (Raheem and Omar, 2021), which exhibited the highest percentage of sand in the middle and western zones. The silt content was notable across all areas, with the southern region registering the highest silt content, as shown in Figure 6. While the study by (Raheem and Omar, 2021) found the highest percentage of silt in the central northern zone of Kirkuk City soil, the investigation presented in this paper showed higher results in other zones. The clay content exhibited a linear correlation with the Atterberg limits, as demonstrated in Figures 7, 8, 9 and 10 with the liquid and plastic limits increasing as the clay concentration increased. The dry density values mostly ranged between 1.373 and 1.75 g/cm³, with the northwest region having the highest percentage, as indicated in Figure 11. Figure 12 shows the significant water content proportions across many locations. Furthermore, Figure 13 reveals that the northeast and east regions of the city had a greater proportion of specific gravity than did the other areas.

Verification of the spatial distribution

The cross-validation method is employed to gauge the accuracy of interpolation methods by testing them at known sample sites, where the

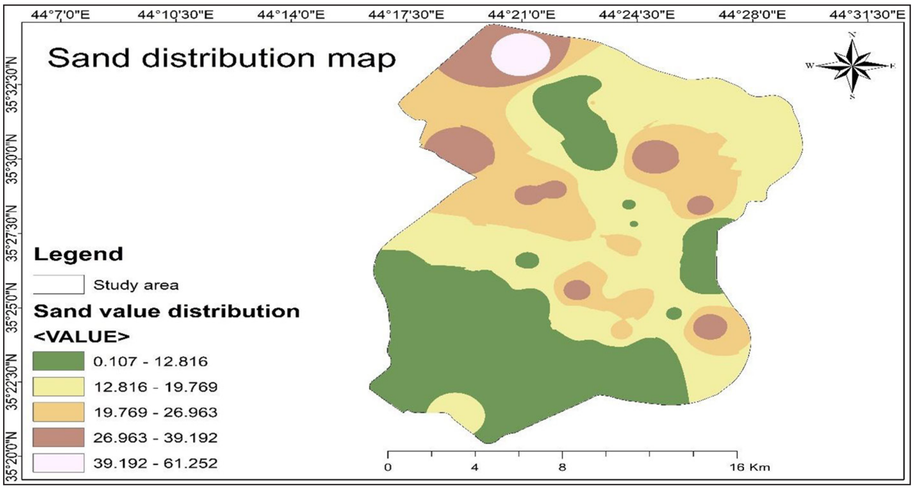

Figure 5. IDW representation of the sand content value

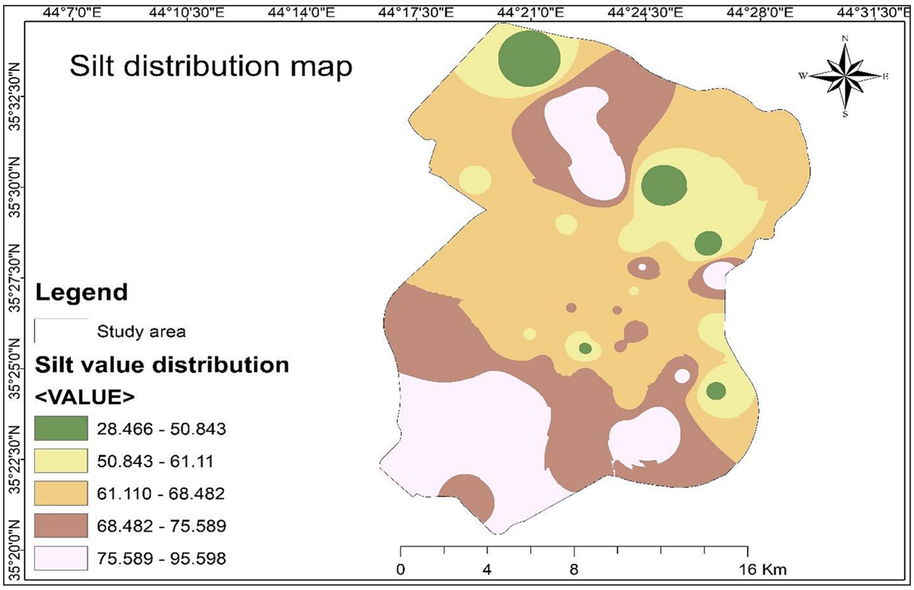

Figure 6. IDW representation of the silt content

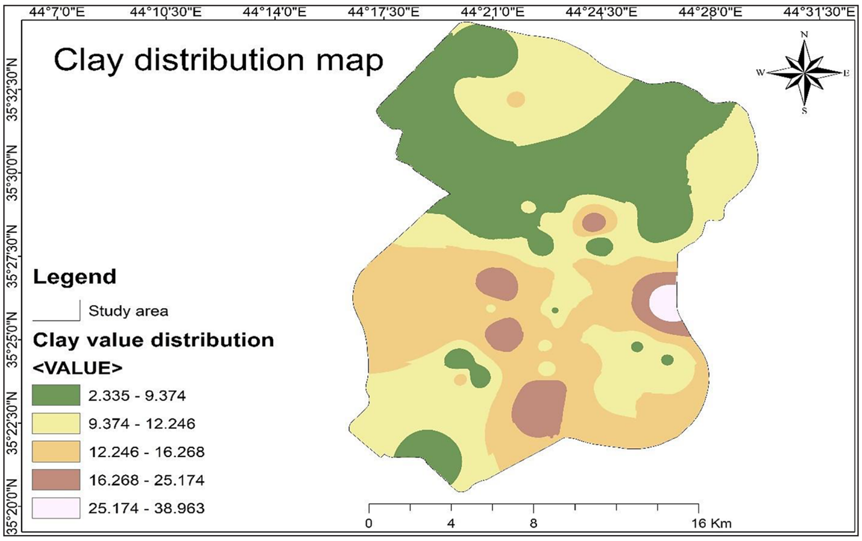

Figure 7. IDW representation of the clay content

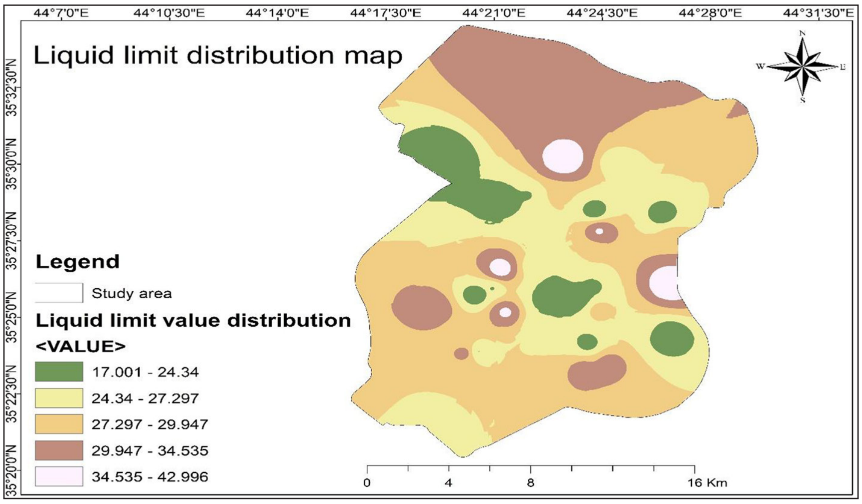

Figure 8. IDW representation of the liquid limit value

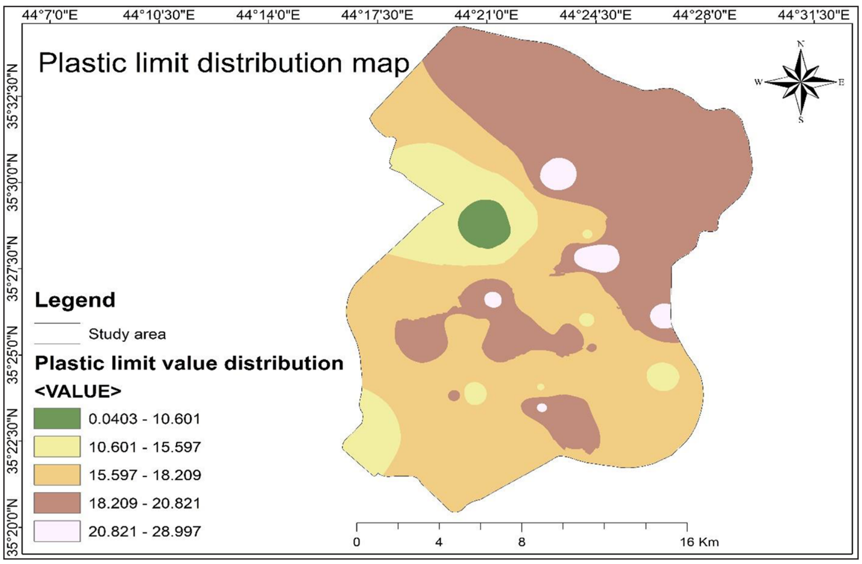

Figure 9. IDW representation of the plastic limit value

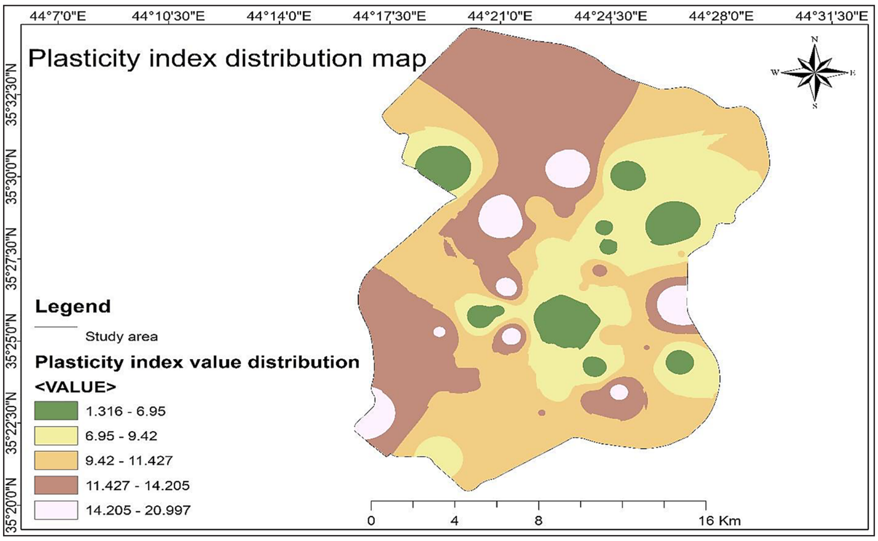

Figure 10. IDW representation of the plasticity index value

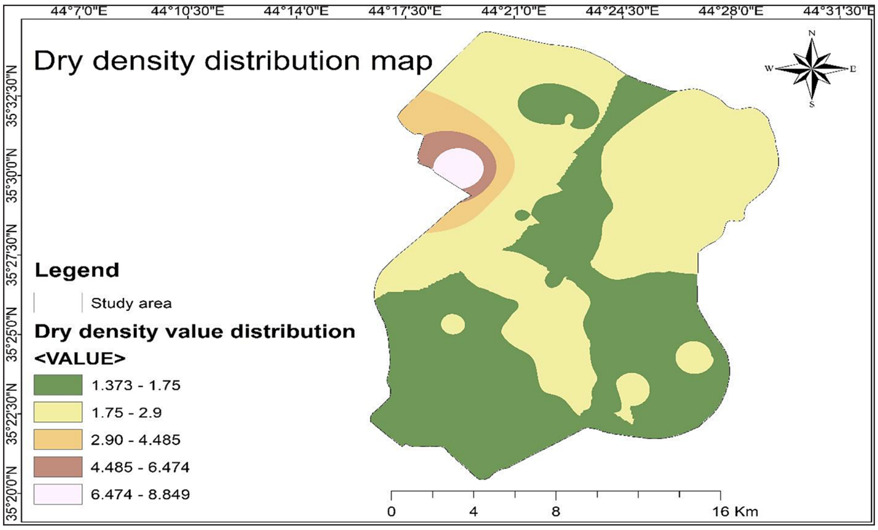

Figure 11. IDW representation of dry density values

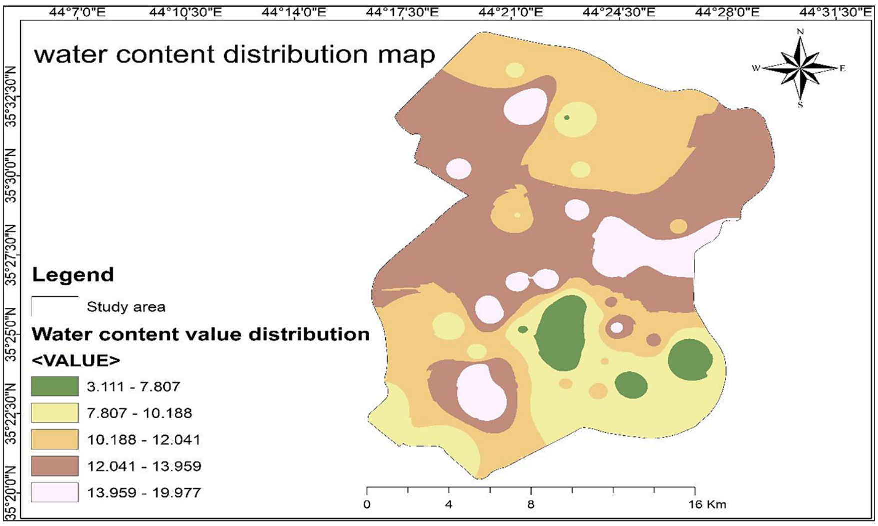

Figure 12. IDW representation of the water content value

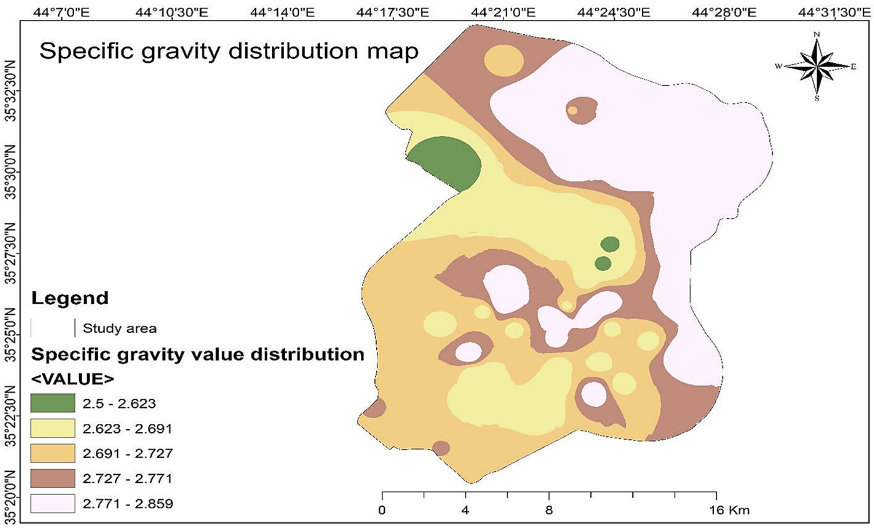

Figure 13. IDW representation of the specific gravity value

estimation method is removed from the dataset and the remaining samples are used to determine values (Yao et al., 2013). This process involves comparing the real sample values with the estimated values to calculate the difference in error, thus evaluating the accuracy of each interpolation method. This validation process is iterated for each available sample (Yao et al., 2013). To verify the accuracy of the IDW-based maps illustrating the physical characteristics of the soil in Kirkuk city, a test dataset comprising 30% of the soil samples was utilized (Veyan et al., 2018). The objective was to compare the field values with the values predicted by the IDW approach. To assess the discrepancy between the observed values and IDW-determined values, metrics such as the root mean square error (RMSE) and R^2 were computed (Veyan., 2018). The choice of interpolation method depends on the amount of data available in a research region. To identify the most effective interpolation technique, various methods were applied to generate the maps depicting the physical attributes of the soil of Kirkuk city. RMSE, as the primary cross-validation criterion, accounts for extrema and stationary points, aiding in the evaluation of interpolation accuracy (Dinget al., 2011). It may be computed as follows:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(Z_i - Z)^2} \quad (2)$$

where: n – the number of values utilized for the estimation, m – the number of selected parameters in the empirical equation, Z is the estimated value, and Z_i is the measured value at the sampling point $i(i = 1,..., n)$(Ding et al., 2011).

The root mean square (RMSE) was used to determine the map accuracy. The most appropriate and accurate way to create maps was the IDW approach (Veyan et al., 2023). Because the R

Table 2. (RMSE) and R^2 for maps

Physical properties	RMSE	R^2
Water Content	0.9066	0.9811
Dry density	0.5003	0.0001
Liquid limit	1.0867	0.945
Plastic Limit	0.9102	0.846
Specific Gravity	0.0868	0.1854
Gravel	1.5993	0.9338
Sand	1.6577	0.9891
Silt	1.0833	0.9984
Clay	1.4613	0.9745

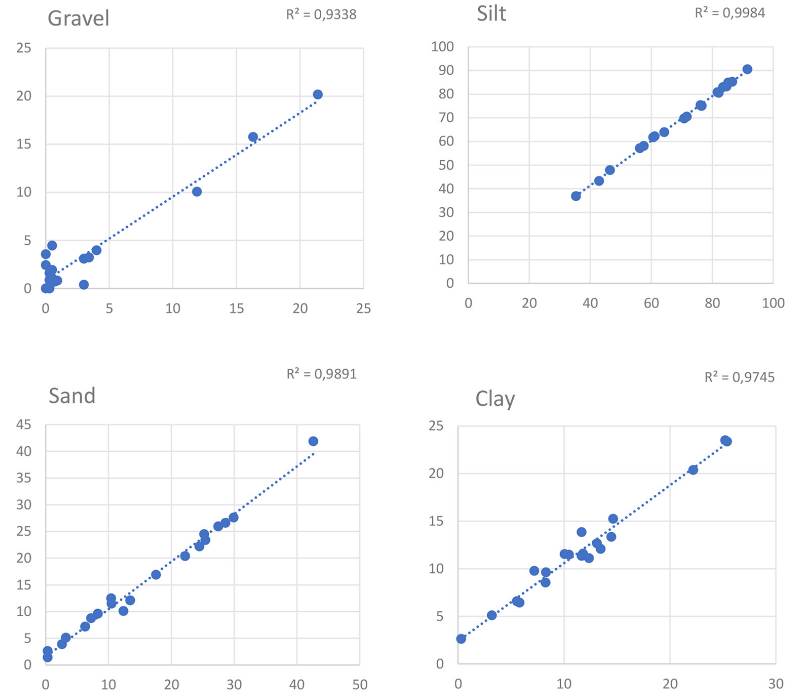

Figure 14. Results of the R square (R^2) values of the gravel, sand, silt, and clay

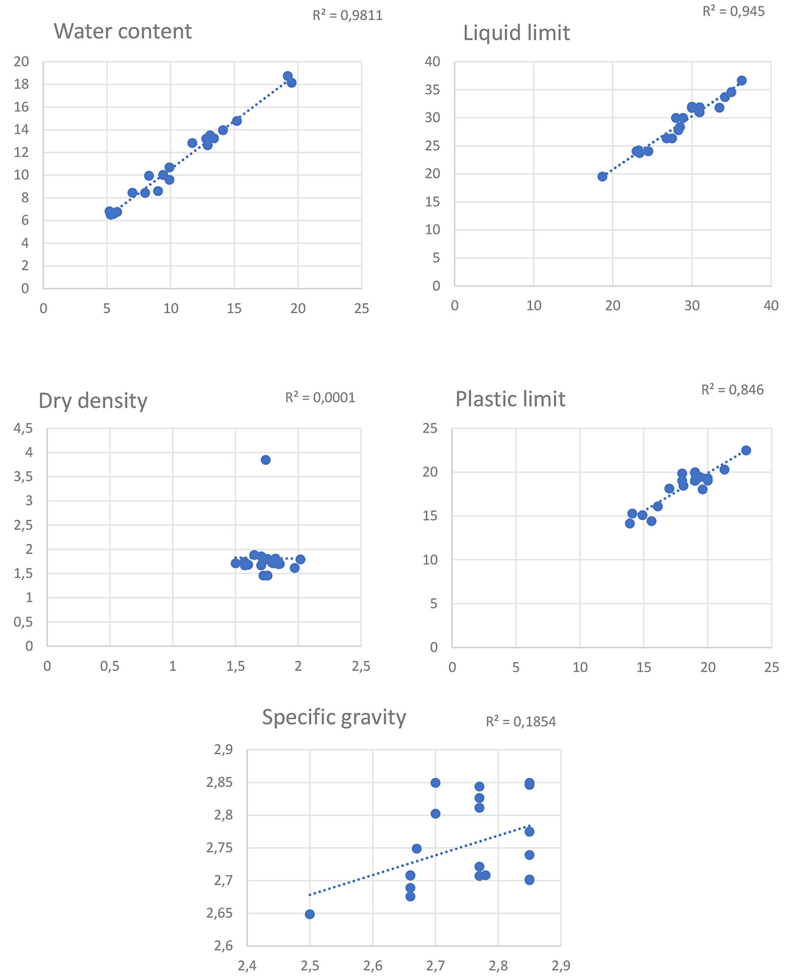

Figure 15. Results of the R square (R^2) values of the water content, dry density, specific gravity, liquid limit, and plastic limit

squared (R^2) is a commonly used goodness-of-fit metric, applied researchers are well aware of its limitations and usefulness (Cameron and Windmeijer, 1997). A better prediction accuracy is shown if the RMSE of physical attributes and R^2 are low. RMSE varied from 0.0868 to 1.6577, and IDW R^2 varied from 0.0001 to 0.9984, as shown in Figures 8 and 9. The results of RMSE and R^2 are shown in Table 2.

CONCLUSIONS

A comprehensive collection of 65 soil samples was conducted throughout Kirkuk city to determine the physical properties of the soil for detailed analysis. This examination aimed to unveil the behavior of the soil, providing valuable insights for geotechnical and engineering practices in the region. The findings from this study can be summarized as follows:

The analysis encompassed 10 spatial maps showing the distribution of various soil types across Kirkuk city, including gravel, sand, silt, clay, specific gravity, Atterberg limit, dry density, and water content. By utilizing the IDW technique, distinct spatial distribution patterns were revealed, revealing variations in property composition across different sectors within the study area.

Notably, specific districts in Kirkuk city exhibited the highest gravel content, as visually represented on digital maps. In particular, the northeast zones had the highest percentages of gravel, while the sand content predominated across most districts. Conversely, the silt content was widespread, displaying a notable range from 28.52% to 95.61% across all samples. Additionally, the clay content was concentrated in the eastern zone and some southern regions of Kirkuk city, with areas rich in silt deemed suitable for agriculture and areas high in clay effective as barriers against heavy metal contamination.

A direct correlation between the clay content and Atterberg limits was observed, with the liquid and plastic limits showing an incremental trend corresponding to an increase in the clay content.

This study utilized an HS-5001EZ moisture density meter to assess the dry density of the soil samples, which ranged from 1.373 to 8.85 g/cm^3. Notably, the southern region exhibited a lower dry density than the northern region. Conversely, the water content was relatively high across all areas, except for specific locations.

The specific gravity values remained consistent across most regions under examination. The coefficient of determination (R^2) for the IDW maps of physical attributes ranged from 0.00041 to 0.9984, predictions with higher values are more accurate, indicating successful predictions for the factors assessed. Additionally, the RMSE ranged from 0.0868 to 1.6577 for the IDW maps, with lower value indicating more accurate predictions.

With accuracy ranging from good to outstanding, the IDW approach successfully mapped the distribution of the various soil properties inside Kirkuk City. Overall, GIS techniques have demonstrated significant effectiveness in modeling and quantifying the physical characteristics of the soil in the study region. The utilization of IDW interpolation offers benefits in protecting and improving soil health through the implementation of effective soil management strategies and treatments.

Fieldwork was conducted at remote sites that were not reachable during this investigation. In order to achieve more reliable results, it would be beneficial for future studies to choose a larger number of sample sites in appropriate places. It is also possible to compare this approach with alternative approaches, particularly those that could be useful in investigating the characteristics and predicting the soil.

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