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Pedogenic Development and Mineralogical Characteristics of Sedimentary Soil Pedons

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Abstract: The study focus on determining the pedogenic development, mineralogical and micromorphological characteristics of sedimentary soils in northern Iraq. Four soil pedons had been selected around Mosul Dam Lake in northern Nineveh province, to represent these soils. The main objective of this study was to determining some of the mineralogical and development characteristics of sedimentary soils in these sites. The process involved a morphological description of soil pedons in the sites, laboratory analyses to determine the physical and chemical properties of soil samples, XRD analysis of clay minerals, and thin section analysis for soil micromorphology. The results indicated That the soil textures were clay, silty clay and clay loam, with the variations in physical and chemical and morphological characteristics of studied sites. whereas, thin section analysis revealed carbonate and gypsum nodules, clay masses, and dissolution voids, indicating transmission and accumulation processes. XRD analysis identified a mixed mineral assemblage consisting of chlorite, illite, palygorskite, montmorillonite, and gypsum. The occurrence of palygorskite under alkaline and moisture-deficient conditions reflects pedogenic processes typical of semi-arid environments (Azimi et al, 2025). Therefore, these findings provide new insights into soil genesis and mineral transformation in northern Iraq and contribute to the sustainable management and conservation soil resources in semi arid zones.

Keywords: Sediment soils, XRD analysis, Micromorphological characteristics

Introduction

The sediment soils of northern Iraq have unique properties influenced by semi-arid climatic conditions, it were formed as a result of fluvial and wind deposition of clastic materials originating from the surrounding mountain ranges, particularly in the Tigris basin and foothill areas (Aziz et al., 2009; Sissakian et al., 2025). Most of these sediments are composed of limestone, marl, and gypsum (Khalaf et al, 2024; AlQaisi et al., 2026). These soils play a fundamental role in agricultural productivity, environmental sustainability, and land use development (Sardoo et al., 2023; Al baghdady & Alabadi, 2021; Al-Badrani & Al-Khafagi, 2025; Altaee et al., 2025). The geological and climatic diversity of the region has contributed to make a significant spatial variability in their physical, chemical, mineralogical, and morphological characteristics, including differences in texture, fertility, and clay mineral composition (Husein et al., 2017; Kaletova et al., 2022). Soil formation and pedogenic development in semi-arid regions is often influenced by interaction between parent material mineralogy and the prevailing moisture regime. Despite of some studies being conducted on these soils, detailed investigations into the micromorphological fabric and clay mineral stability are limited (Horváth et al., 2016). The development of sediment soils in semi-arid regions is governed by numerous environmental conditions, including climate defined by annual rainfall, temperature average, wind intensity and direction (Nortcliff, 2009; Verheye, 2009).

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Topography also plays a significant role, along with human activities such as tillage systems and irrigation methods, as well as the impact of soil parent material (Blume et al., 2002; Azimi et al., 2025). In general, soil development is a result of soil forming factors and processes over time, which include the weathering of geological materials and their transformation under new conditions into new products that are similar to or different from the parent material, and the degree of soil development depends on the intensity of influencing factors and the type of parent materials, (Nesbitt & Young, 1996; Silva et al., 2025). However, the processes of soil formation and development are numerous and complex, no one process can be given priority over another, and these processes proceed in a specific direction and under specific conditions, and the final result is the formation and development of the soil (Bockheim et al., 2014). The development of soil profiles includes the weathering of clay minerals and their transformation it from primary to secondary minerals, interspersed with processes of transport and deposition of mineral components between the horizons of soil profiles (Al-Khalaf & Al-Saad, 2017; Khalid, 2019). Clay minerals are the most active component of soil minerals, such as Mica, Chlorite, Illite, Montmorillonite, Kaolinite, Palygorskite, Gypsum, Vermiculite and others, making their chemical, physical, and micromorphological properties a significant factor of many soil characteristics (Usul & Dengiz, 2010; Heeshan et al., 2022; Alhadede et al., 2025). X-ray diffraction is the most common and accurate method for characterizing the mineral composition of clay particles and detecting clay minerals in soil, both quantitatively and qualitatively (Zhou et al., 2018). XRD is available technology to identify and measure all minerals present in clay-rich rocks such as mudstone, shale, and marls (Srodoi et al, 2001; Remigio et al., 2022). The study of soil micromorphological characteristics is an essential tool for understanding the degree of change that occurs within soil pedons as a result of pedogenic processes, soil development, human activities, and the influence of soil organisms (Ismael, 2022). Micromorphological investigations provide valuable information on soil genesis, mineral composition, and the mechanisms involved in soil formation and evolution (Jahan & Manafi, 2018). These characteristics are commonly examined using thin-pedon techniques under optical or electron microscopes, allowing detailed observation of soil constituents and their spatial relationships in three dimensions. Such analyses contribute significantly to the assessment of biogenic features and the interpretation of soil-forming environments and processes (Dincă et al., 2022). Therefore, this study aimed to: [1] identify the different properties of sedimentary soils in selected areas of northern Iraq. [2] Assessing the pedogenic development of soil pedons. [3] determine the micromorphological and mineralogical characteristics of soil pedons.

Materials and Methods

The Studied Sites Description

This study was conducted on the sedimentary soils surrounding Mosul Dam lake, which is located to north of Nineveh province, Iraq. The study area are located within semi-arid zones, and these soils were classified into Aridisols and Inceptisols orders according to USDA (Soil Survey Staff, 2006). Four soil pedons were chosen and randomly distributed around the lake (Figure 1), to represent all directions (north, west, south and east). Soils of the study area are characterized with difference of parent material, as gypsum, limestone and marls constitute the majority of it (Issa et al., 2014). Land in the study area is flat to a slight slope, the vegetation consists of wheat, barley, and vegetable crops.

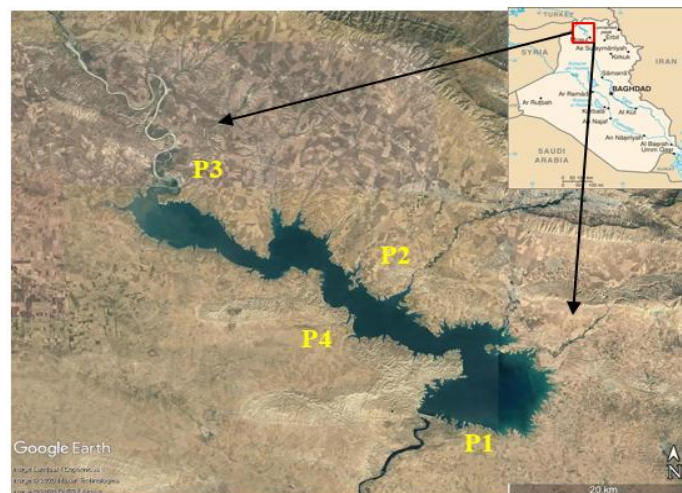


Figure 1. The map of study sites

Table 1 shows the informations (the coordinates, the elevation and the vegetation) of soil pedons, the symbols P1, P2, P3 and P4 were assigned to represent first, second, third and fourth soil pedons respectively. The climate of the study area is characterized by variations in average temperatures throughout the year. In Summer, the temperatures ranged between (30-45) °C, while in winter, the temperatures ranged between (0-12) °C. This climate is generally considered the Mediterranean. The average annual rainfall is between (150-400) mm, and the periods of rainfall are concentrated during winter and spring seasons.

Table 1. The information of soil pedons

Pedon	Coordinates		Elevation (m)	Vegetation
	N.	E.		
P1	36.609779°	42.903001°	327	wheat
P2	36.691454°	42.938047°	332	vegetable crops
P3	36.764594°	42.755139°	330	vegetable crops
P4	36.717219°	42.734122°	329	barley

Field Work and Morphological Description

Four soil pedons (P1, P2, P3 and P4) were excavated, and the soil profiles that direct sunlight were characterized into horizons, and described morphologically according to USDA (Table 2). Undisturbed soil samples were collected from subsurface horizons (B horizons) for thin pedons preparation and micromorphological analysis. In addition, soil samples were collected from all horizons (12 soil samples), then the samples were placed in labeled plastic containers and subsequently transported to the laboratory for analyses.

Table 2. Morphological properties for soil pedons

Pedon	Horizon	Depth (cm)	Soil color			Structure	Consistency	Boundary
			dry		wet			
P1	A _p	0-20	10YR 5/3	b	10YR 3/3	db	Bfsa	SFpl c
	B	20-47	10YR 5/4	yb	10YR 4/4	dyb	Bmsa	SFpl c-w
	C _k	47-100	10YR 7/4	ypab	10YR 4/4	dyb	Bma	SFspl w
P2	A _p	0-8	10YR 5/3	b	10YR 4/3	b	Bfsa	SFpl c-w
	B	8-38	10YR 5/4	yb	10YR 3/3	db	Bma	SFpl c-w
	C	38-95	10YR 5/6	yb	10YR 4/6	dyb	Bma	Shp w
P3	A	0-12	10YR 6/4	lyb	10YR 4/4	dyb	gfm	Shpl w
	B	12-57	10YR 5/4	yb	10YR 3/3	db	Bma	SFpl c-w
	C _k	57-100	10YR 5/3	b	10YR 3/3	db	Bma	SFpl w
P4	A _p	0-15	10YR 6/4	lyb	10YR 4/4	dyb	Bfm	FSpl w
	B	15-48	10YR 5/3	b	10YR 3/3	db	prma	Shpl w
	C	48-95	10YR 5/3	b	10YR 3/3	db	Bma	SFpl w

Notes: l=light, y=yellowish, b=brown, d= dark, pa=pale;; B=blocky, f=fine, sa=subangular, m=moderate, a=angular, pr=prismatic, g=granular : S=Slightly, h=hard, F=friable, pl=plasticity, s=sticky.; c=clear, w=wavy.

Laboratory Work

Disturbed and undisturbed soil samples were prepared for the physical and chemical laboratory analyses, that following: particle size distribution, bulk density, soil pH, soil EC, O.M., CEC, CaCO₃, and CaSO₄.2H₂O, analytical procedures were carried out according to (Rowell, 1994).

Preparation of Soil Thin Pedons

Thin pedons thick (30 µm) were prepared from undisturbed soil samples collected from B horizon of each soil pedon. Micromorphological observations were conducted using a polarized transmitted light microscope (Leitz Laborlux S model) at 40× magnification. Soil constituents and micromorphological features, including voids, mineral crystals, and soil aggregates, were characterized according to the methods described by FitzPatrick (1981).

Soil Mineralogical Analyses (XRD)

The clay particles present in the soil samples of B horizon for all soil pedons were separated from other soil components (sand and silt) in the laboratory by precipitation according to Stokes' law, the carbonates, soluble salts, organic matter, and iron oxides have been removed (Moore & Reynolds, 1997). Approximately (30) mg of clay sample was placed on a (2.6 × 2.3) cm glass slide, then these samples were analyzed using the X-ray diffraction instrument (XRD-6000, Shimadzu, Japan). Clay samples that loaded on the glass slides have been subjected to the following treatments prior to XRD analysis (Al-Rawas et al., 1998):

- Mg-saturated, air-dried.
- Mg-saturated, ethylene glycol.
- K-saturated, air-dried.
- K-saturated, heated at 350 C°.
- K-saturated, heated at 550 C°.

Results and Discussion

Physical and Chemical Characteristics for Soil Pedons

Table (3) shows some physical and chemical characteristics of soil pedons in the studied sites, it is note that there variations within horizons and soil pedons. The particle size distribution results showed that the soil texture were clay (C), clay loam (CL), and silty clay (SC), sand particles content ranged between (185-242) g kg⁻¹ in horizon C of P3 and the surface horizon A of P2 respectively, silt particles ranged between (295-411) g kg⁻¹ in horizon C of P2, and horizon A of pedon P3 respectively, whereas the clay particles ranged between (375-500) g kg⁻¹ in horizon A of P3 and horizon C of P2. These variations may be attributed to parent materials nature, intensity of weathering processes, and soil forming and development processes in the studied sites (Kabi & Jena, 2025).

Table 3. Physical and chemical characteristics for soil pedons

Pedon	Horizon	Depth (cm)	particles size distribution g.kg ⁻¹			Texture	Bulk density Mg.m ⁻³	pH	EC ds.m ⁻¹	g.kg ⁻¹			CEC cmol.kg ⁻¹ soil
			sand	silt	clay					O.M.	CaCO ₃	CaSO ₄	
P1	A _p	0-20	196	400	404	SC	1.47	7.70	1.18	18.00	203	13.63	25.22
	B	20-47	193	389	418	C	1.52	7.90	0.70	16.12	191	13.50	21.39
	C _k	47-100	214	375	411	C	1.41	7.70	0.47	10.14	235	16.81	20.00
P2	A _p	0-8	242	378	380	CL	1.45	7.80	0.85	19.50	186	12.15	26.50
	B	8-38	191	390	419	C	1.56	7.60	0.62	14.33	200	11.85	23.68
	C	38-95	205	295	500	C	1.60	7.80	0.49	10.52	228	15.47	20.62
P3	A	0-12	214	411	375	CL	1.44	7.90	1.21	17.40	184	14.63	23.41
	B	12-57	194	386	420	C	1.53	7.70	0.71	13.82	219	11.77	18.37
	C _k	57-100	185	393	422	C	1.59	7.50	0.50	8.65	227	12.74	17.54
P4	A _p	0-15	192	403	405	SC	1.46	7.90	1.00	20.13	193	10.42	24.71
	B	15-48	206	410	384	CL	1.50	7.70	0.62	12.50	197	10.66	22.45
	C	48-95	200	338	462	C	1.57	7.60	0.70	9.12	228	13.80	20.36

Notes: SC= Silty Clay, C= Clay, CL= Clay Loam.

Bulk density values ranged between (1.41-1.60) Mg.m^{-3} in horizon C of P1 and horizon C of pedon P2 respectively. Generally, bulk density tended to increase with depth, which can be attributed to lower organic matter content, increasing clay content, and reduced biological activity in subsurface horizons, while the lower bulk density values in surface horizons are associated with organic matter accumulation and better soil aggregates. Such conditions enhance soil porosity, water infiltration, and root penetration. Soil pH values ranged between (7.50-7.90), indicating that all studied soils were neutral to slightly alkaline, that is due to the high CaCO_3 content in the studied soils. Soil EC values at generally, were relatively low of all sites, the values ranged between (0.47-1.21) dS.m^{-1} in horizon C of P2 and the horizon A of P1 respectively. Soil O.M. content showed considerable variation among the horizons, ranging from (8.65) g kg^{-1} in horizon C of P3 to (20.13) g kg^{-1} in horizon A of P4. In general, organic matter content was highest in the surface horizons and decreased progressively with depth. This distribution pattern reflects the accumulation of plant residues and greater biological activity in soil surface, differences along pedons may also be related to variations in vegetation cover and environmental conditions. CaCO_3 content of studied soils ranged between (184-235) g kg^{-1} , with the lowest value recorded in horizon A of P3, while the highest value was recorded in horizon C of P1. Moreover, soils of these areas are characterized by an abundance of lime as a natural result of the parent material, climate and environmental conditions of these soils containing calcite minerals, which is the main component of limestone. It was noted that CaCO_3 increased with depth in the most of soil pedons (Li et al., 2021). Similarly, $\text{CaSO}_4.2\text{H}_2\text{O}$ content showed a slight increase with depth of soil pedons, it was ranged between (10.42-16.81) g kg^{-1} in horizon A of P4 and the horizon C of P1 respectively. In general, the distribution of gypsum is also influenced by the mineralogical composition of parent material and environmental conditions. While CEC values ranged between (17.54-26.50) cmol.kg^{-1} soil, in horizon C of P3 and horizon A of P2. These values have been associated with the clay and organic matter content along the horizons of soil pedons in studied sites. In addition, CEC has a clear influence in determining soil fertility and the content of nutrients necessary for plants.

Thin Sections of Soil Pedons

The results of micromorphological analyses (using a transmitted polarized light microscope) of undisturbed soil samples, obtained from subsurface horizon (B horizon) of all studied pedons, showed variation in the nature of micromorphological characteristics, including nodules, voids, and aggregate shapes. These features indicate the activity of some pedogenic processes responsible for soil formation in the study area, especially the processes of loss and gain of some soil components. Figure (2) indicates that the soil in this site is composed of sedimentary rocks of calcareous and gypsum origin, as evidenced by the presence of carbonates remnants and gypsum minerals, this results was consistent with the chemical and morphological properties of this soil pedon.

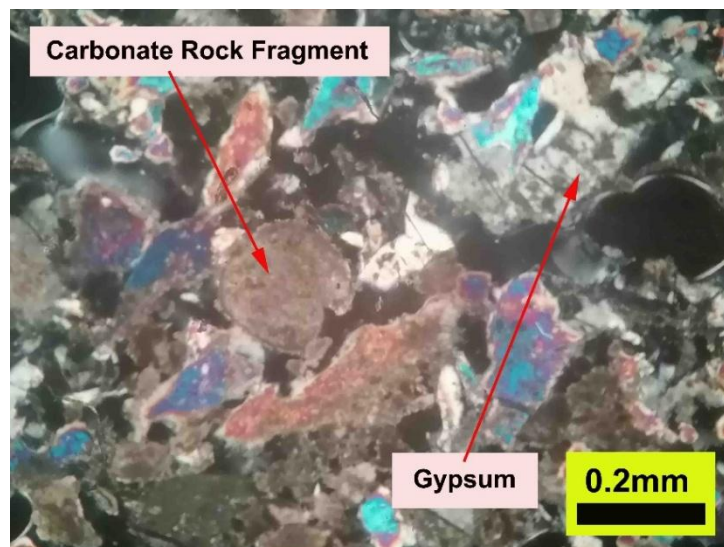


Figure 2. Thin section for soil P1

A figure also shows voids or cavities measuring (0.3 mm), which indicate the dissolution of minerals by rainwater or by plant roots growing in the soil. The presence of carbonate and gypsum minerals in the soil affects some of its chemical properties, such as its pH level and some of its fertility characteristics, in addition to physical properties such as permeability, structure, and aggregation. Figure (3) shows the presence of silicate clay minerals, specifically feldspars, which are aluminum silicates containing calcium and sodium between their

layers. It also shows the presence of clay masses, indicating the accumulation of clay minerals within the soil body, this result was consistent with the results of (Alhashyme & Khaled, 2025). Furthermore, the figure clearly shows the presence of carbonates and the distinctive forms of gypsum minerals ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) in this horizon, and the predominant type of structure in the soil sample is crumb and granular.

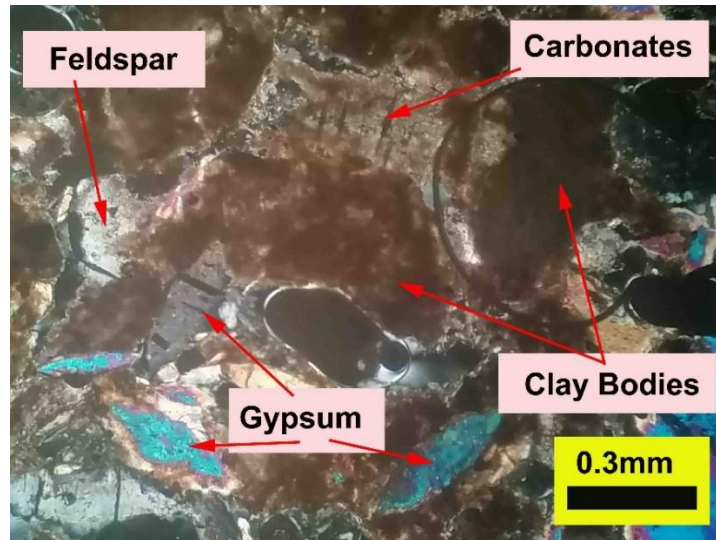


Figure 3. Thin section for soil P2

These results reflect the pedogenic processes under which this soil has been formed. The results of the analyses in Figure (4) showed the presence of quartz, indicating the presence of silica at this site, in addition to clay minerals inherited from the original sedimentary material. Quartz is characterized by its hardness and relatively high resistance to chemical weathering processes, and this mineral influences the physical properties of the soil. The soil at this site also exhibits vugs with different sizes, which further indicate the dissolution and leaching of some soil components to deeper horizons by water.

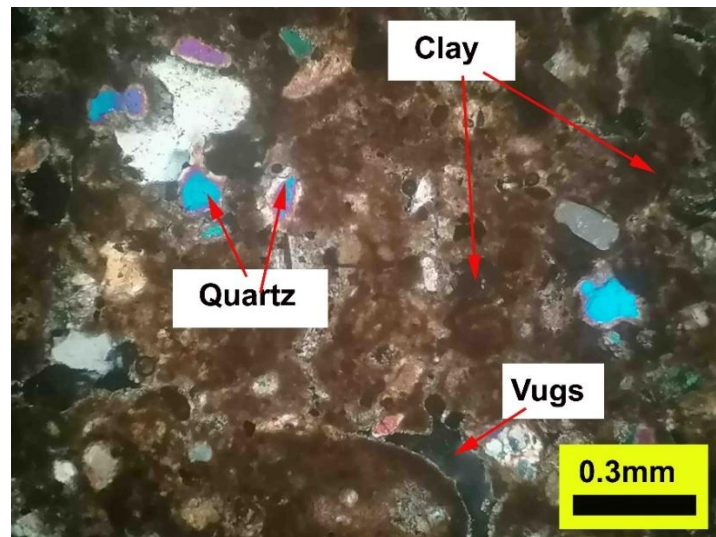


Figure 4. Thin section for soil P3

Figure (5) shows the carbonate and gypsum groups, in addition to clay and various voids. These results reflect the state of the interconnected influence of the main soil components, especially the lime and gypsum content in this horizon, and the influence of the environmental factors surrounding those soils, in addition to the basic role in the activity of some pedogenic processes responsible for the formation of those soils. These processes indicate the occurrence of a movement of transport and deposition of mineral and organic materials (Soil plasma) with a size of soil colloids (less than 2 microns) within the soil, with the availability of the transporting agent represented by water (Owliaie & Abtahi, 2006).

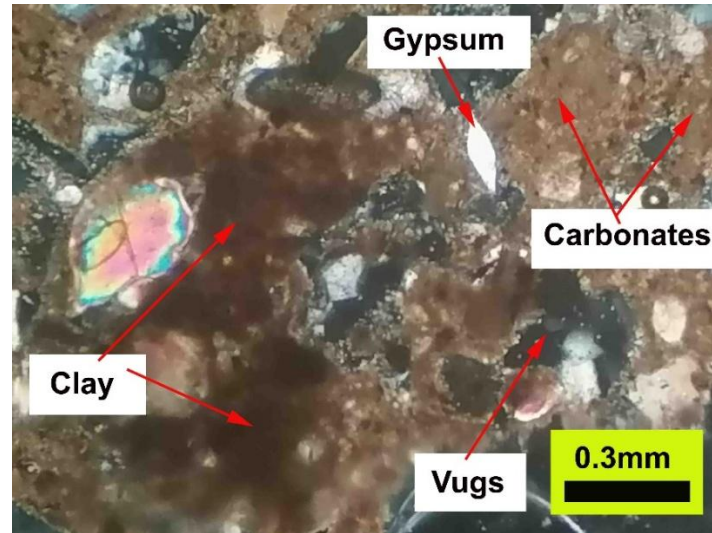


Figure 5. Thin section for soil P4

XRD Analyses for Soil Pedons

Figures (6-9) showed the XRD curves of clay samples taken from B horizon for each soil pedon, which were treated according to the treatments mentioned previously for Mg and K. The XRD analysis revealed the presence of a group of minerals represented by chlorite, illite, palygorskite, montmorillonite and gypsum, this mixture of minerals is specifically a characteristic feature of soils in semi-arid climates. Figure (6) showed the presence of chlorite at the (14.7°) inversion, which remained stable upon heating up to 550°C , (10.4°) peak and partial collapse upon heating of the K-saturated layer indicate the presence of palygorskite with thin montmorillonite layers. Illite appeared at diffraction (10°) in (Mg-air dry) treatment.

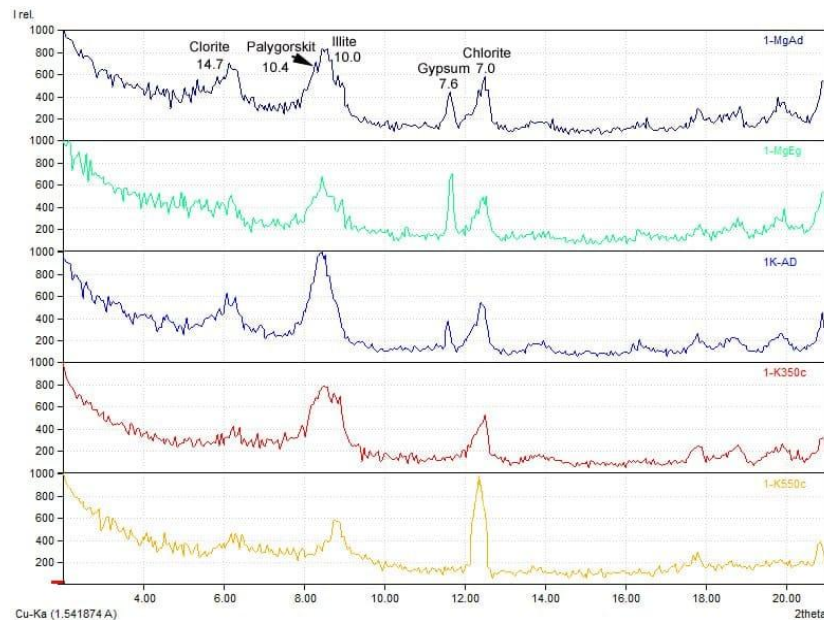


Figure 6. XRD analysis for soil P1

Gypsum (7.6°) is present alongside the palygorskite, indicating its concentration by evaporation under alkaline conditions rich in Mg and silicon (Khormali et al, 2003; Al-Mallah et al, 2016). This composition is consistent with soil formation models in the semi-arid regions of northern Iraq, where palygorskite forms spontaneously in gypsum-rich subsurface layers under conditions of soil moisture deficiency. Figure (7) showed the XRD analysis of soil pedon (P2) clay sample, that the montmorillonite appeared with chlorite at diffraction (14.7°) in the (Mg-ad) treatment, then it expanded at diffraction (17.7°) in the (mg-Eg) treatment. The palygorskite (10.4°) reflection coincides with the gypsum (7.64°) reflection, while chlorite is clearly visible at (7.0°) and (14°).

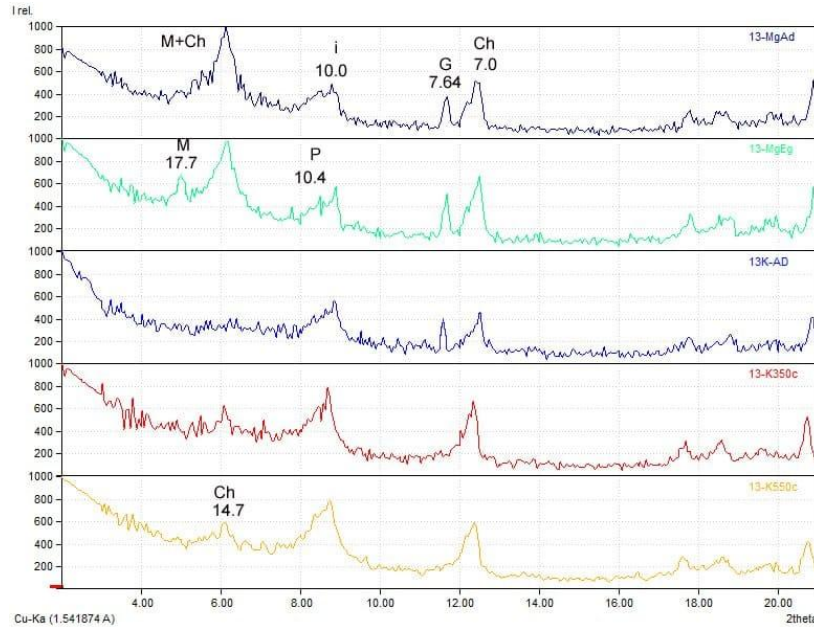


Figure 7. XRD analysis for soil P2

Gradual heating with K to 550 C° leads to the decomposition of montmorillonite, while palygorskite and chlorite remain stable, indicating the presence of a mixed assemblage of montmorillonite, palygorskite, chlorite, and gypsum, a characteristic feature of soil formation in semi-arid and low-moisture regions. In Figure (8), the peak of 17.7A° after treatment with Mg-eg confirms the presence of montmorillonite, while palygorskite persists within the 10.4 A° inversion and gypsum within the 7.64 A° inversion. Chlorite is identified by the stable peaks of (14.7A° and 7.0 A°) up to 550 C°. K-saturation and gradual heating to 550 C° lead to the decomposition of montmorillonite, but do not affect palygorskite and chlorite, indicating the presence of a mixture of soil minerals (montmorillonite-palygorskite-chlorite-gypsum) that formed under alkaline conditions with the influence of seasonal wetting and drying cycles (Song et al., 2020). Figure (9) showed appeared of a peak with (17.7A°), unequivocally indicating montmorillonite with (Mg-eg). The 10.4 A° and 7.66 A° reflections correspond to palygorskite and gypsum, respectively. Chlorite is identified in 14.7 A° and 7.0 A°, which persists after K-550 C°. The thermal stability of chlorite and palygorskite contrasts with the complete collapse of montmorillonite (Emadi et al., 2008).

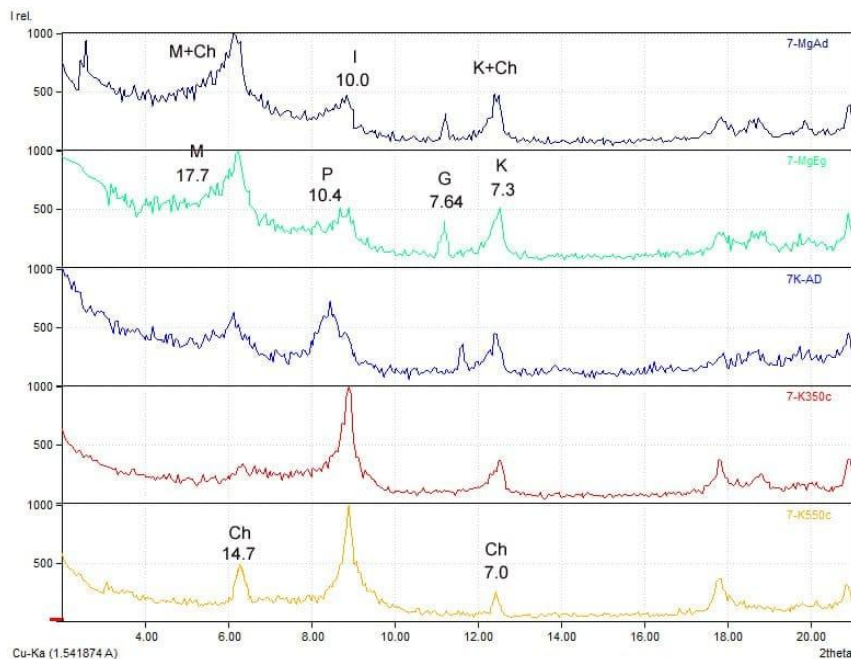


Figure 8. XRD analysis for soil P3

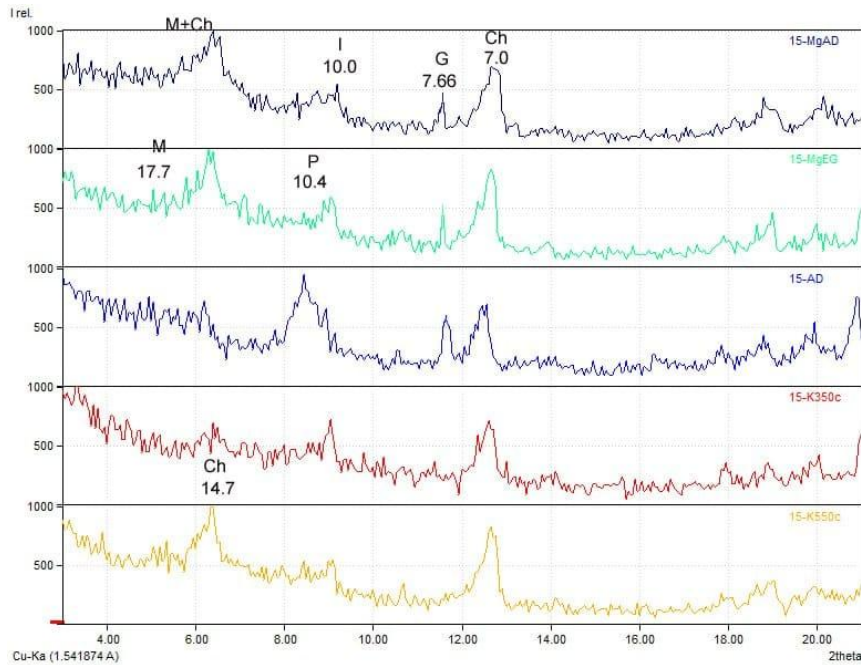


Figure 9. XRD analysis for soil P4

Conclusion

This study provided an important assessment of the developmental degree, micromorphological and mineralogical characteristics of Sedimentary soils of the sites surrounding Mosul Dam lake in northern Nineveh, that classified into Aridisols and Inceptisols orders according to USDA. The study included thin sections and XRD analyses, soil morphological data, and laboratory physical and chemical analyses for 12 soil samples, involved excavating 4 soil pedons, and providing scientific explanations of the processes controlling soil formation and development under semi arid conditions.

The studied soils exhibited variations in physical, chemical, and morphological properties due to differences in the nature of parent materials (calcareous and gypsum), and the impact of soil formation processes. The results indicated that soils texture were clay, silty clay, and clay loam, with variations in CEC, O.M., CaCO_3 , and gypsum content. Thin section analyses using a polarizing microscope of subsurface horizon soil samples revealed the presence of carbonate and gypsum nodules, clay aggregates, and voids resulting from dissolution of the gypsum and carbonates. These formations are influenced by Translocation and deposition processes, and redistribution of the soil components within pedon horizons. These characteristics explain the chemical weathering impact on the secondary minerals' formation, and the clay accumulation indicates movement of the clay particles through soil horizons under the seasonal rainfall impact, living organisms and the human activities through tillage processes and movement of the agricultural machinery. XRD analyses for clay samples identified assemblage of minerals Represented by chlorite, illite, montmorillonite, palygorskite, and gypsum. with stability of chlorite and palygorskite after thermal treatment, along with the inhibition of expansion and collapse of montmorillonite. The inclusion of palygorskite and chlorite reflects the geochemical conditions and low moisture, characteristics of semi arid environments.

In general, the studied soils represent weak developed soils, resulting in the influence of parent material, climate, and environmental conditions. These findings contribute to a better understanding of agricultural lands in these sites, and provide a scientific basis for soil agricultural management, and the sustainable use of soil resources in the semi arid regions. Furthermore, this study offers valuable insights regarding micromorphological and mineralogical characteristics, and sedimentary soils development, and can form a reference framework for future educational studies in similar areas.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors

Conflict of Interest

* The authors declare that they have no conflicts of interest.

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