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Assessing Soil Weathering and Micromorphological Characteristics under Different Land Use Practices in Northern Iraq

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ABSTRACT

This study investigates the impact of varying land use practices on the micromorphological and chemical properties of soils in the Nineveh Plain region of northern Iraq. Four sites were selected, each comprising three distinct plots: an uncultivated plot, a plot cultivated with vegetables, and a plot planted with wheat. Three of the study sites are located within Nineveh Governorate (Zumar, Rashidiyeh, and Ba'shiqah), while the fourth is situated in Duhok Governorate (Zawita). The primary objective was to assess the degree of soil weathering across these sites, using chemical weathering indices and micromorphological analysis. Thin section images revealed an abundance of small, white carbonate nodules (glaebules) along with sparse, dark carbonate nodules, indicating varying degrees of weathering. The Rashidiyeh site exhibited the highest level of soil weathering, while the Zawita and Zumar regions displayed relatively low weathering intensities. The Chemical Index of Weathering (CIW) proved to be the most reliable indicator for assessing the extent of soil weathering across all sites. These findings highlight the significant influence of land use on soil degradation processes, underscoring the necessity of monitoring chemical and micromorphological changes to predict soil sustainability. The study's results provide crucial insights into the sustainability of agricultural practices in the region, with implications for future land management and soil conservation strategies.

1. INTRODUCTION

Soil properties are influenced by a range of factors, including both natural processes and agricultural practices, which can profoundly affect their structural and physicochemical characteristics. These factors also play a crucial role in determining the sustainability of agricultural production systems [1, 2]. Given that the agricultural sector is fundamental to providing food and raw materials for all human activities, ensuring soil sustainability is of paramount importance [3, 4].

Micro-morphology is a vital tool for understanding the subtle alterations that occur in soil due to human interventions, such as tillage, fertilization, pesticide use, and different irrigation systems [5]. The study of micromorphological features in soils has been paid less attention in the past decades due to the lack of expertise in that field, besides the size of work needed to prepare samples in thin section and microscopy examination [6]. Studies have shown that unsustainable agricultural practices can lead to soil structure degradation, negatively impacting its ability to retain water and nutrients, and consequently affecting crop productivity [5, 7]. These effects include deterioration of soil structural stability, reduced porosity, and increased susceptibility to wind and water erosion [8]. Furthermore, the excessive use of agricultural chemicals disrupts biological activity in the soil, affecting microbial diversity and reducing the soil's capacity to naturally recycle nutrients [9].

On the other hand, adopting sustainable agricultural practices, such as conservation agriculture, organic matter management, and multi-layered agriculture, contributes to improving soil micro-structure, thereby enhancing the sustainability of agricultural production. Conservation agriculture, for instance, helps improve soil structural stability and reduce erosion, leading to enhanced water use efficiency and increased long-term agricultural productivity [10]. In this context, this study aims at (1) quantifying the extent of weathering and micromorphological characteristics of four major soil orders in northern Iraq; (2) exploring how climate (rainfall/temperature) and native soil properties influence weathering processes; and (3) evaluating the effectiveness of different weathering indices in distinguishing between these soil orders.

2. MATERIALS AND METHODS

2.1 Location

Four sites with different orders were selected from northern Iraq (Figure 1). The first site is the Zummar area within the Nineveh Governorate, which represents the Aridisol order.

The second site is the Rashidiya area within the Nineveh Governorate, which represents the Inceptisols order. The third site is the Ba'shiqa area within the Nineveh Governorate, which represents the Vertisols order. The fourth site is the Zawita area within Duhok Governorate, which represents the Mollisols order. In each location, the first is in an area that is not cultivated, the second is in an area planted with vegetables, and the third is in an area planted with wheat. The symbols (Za, Ra, Ba, Zaw) were assigned to the sites of Zummar, Rashidiya, Bashiqa, and Zawita, respectively, while the symbols (P1, P2, P3) were assigned to the uncultivated pedons, the pedons planted with vegetables, and the pedons planted with wheat, respectively. d1 and d2 mean depth 1 and 2. Thus, the total number of pedons in the study became 12 pedons. Table 1 shows the coordinates of the study areas.

Table 1. The coordinates of the study areas

Location	Latitude (DMS)	Longitude (DMS)
1	36°36'17.73"N	42°31'48.76"E
2	36°24'1.33"N	43°3'39.37"E
3	36°29'19.62"N	43°15'40.90"E
4	36°57'54.63"N	43°3'18.10"E

2.2 Climate

The three sites (Zummar, Rashidiya, and Bashiqa) are located within the Nineveh Governorate, which is characterized by a semi-tropical continental climate with differences in temperature and rainfall between the seasons. The average annual temperature ranges from 19℃ to 21℃, and the average annual rainfall is between 340 mm and 400 mm, most of which is concentrated during the winter, while there is almost no rainfall in the summer. As for the site of Zawita, it is located in Dohuk Governorate, where the average annual rainfall ranges between 520 mm and 640 mm, and the average annual temperature ranges from 16.5℃ to 19℃.

2.3 Field work

Soil pedons were dug at the selected sites mentioned above. Then, disturbed and undisturbed soil samples were taken from the existing horizons, and morphology was described according to the method described by the studies [11, 12]. The samples were then transported to the laboratory for the necessary analyses.

2.4 Particle size distribution of soil fractions

Soil texture and its three fractions (sand, silt, and clay) were determined using the hydrometer method, according to the method described by the study [13].

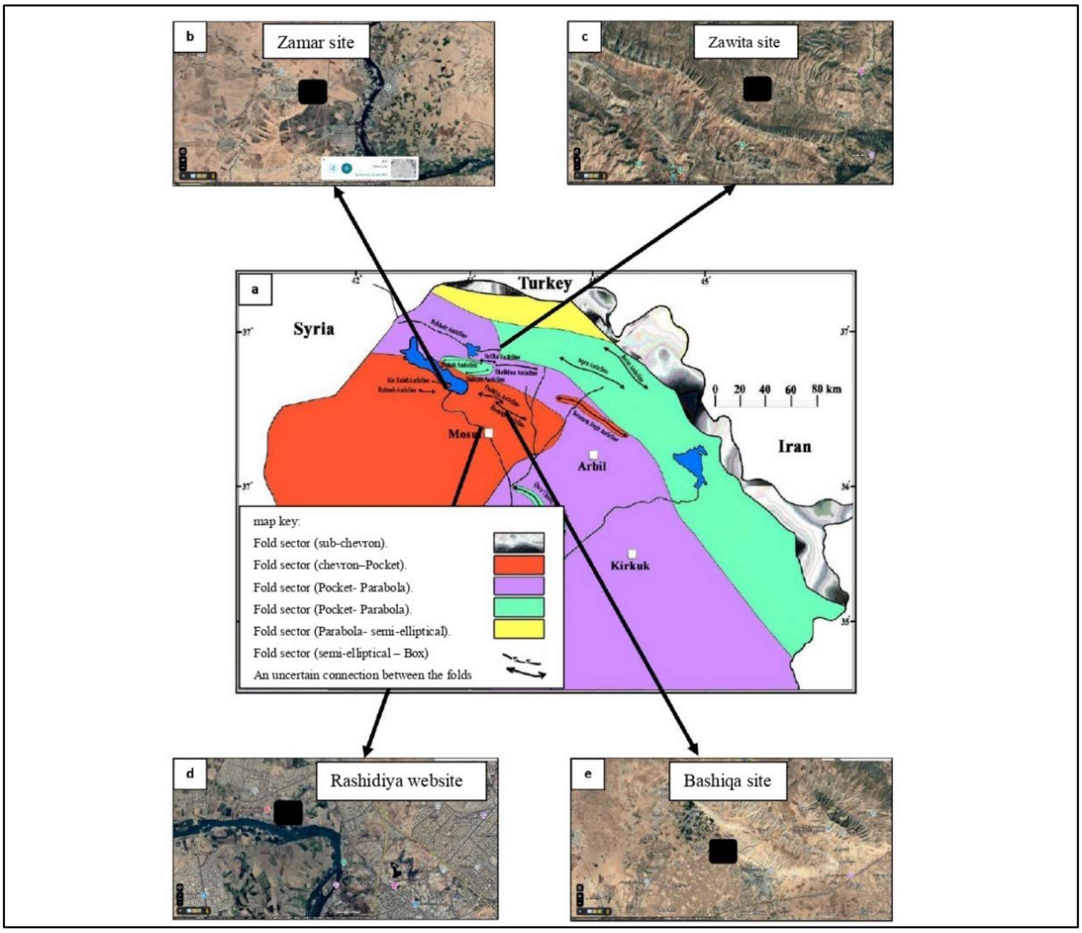

Figure 1. Map showing study locations

2.5 XRF analysis

The elemental analysis of the study samples was performed on their oxides using an XRF device. The analysis focused on Fe_2O_3, SiO_2, Na_2O, K_2O, CaO, MgO, MnO, and TiO_2 in very fine sand particles (50-100 µm) as a method for determining soil homogeneity by calculating the size distribution of weathering-resistant mineral grains based on the Index of Mineral Weathering (Table 2). A separate portion of the soil samples was then collected, ground to a size smaller than 75 µm, and 4 g of this ground sample was mixed with wax to prepare compressed granules in the form of discs. These discs were subsequently placed inside the XRF device (Spectro X-LAB 2000) for analysis. The analysis was conducted in the laboratory of the College of Earth Sciences at the University of Baghdad.

Table 2. Weathering indices used in the analysis

Weathering Index	Definition	Equation	Source
CIW	Chemical Index of Weathering	Al_2O_3 / (Al_2O_3+CaO+Na_2O)*100	[14]
WR	Weathering Ratio	(CaO+MgO+Na_2O) / TiO_2	[15]
WI	Weathering Index	(SiO_2+CaO)/(Al_2O_3+Fe_2O_3+TiO_2)	[16]
Si/Ses	Silica/Sesquioxides	SiO_2 / (Al_2O_3+Fe_2O_3)	[17]

2.6 Thin section preparation

Thin sections, 30 microns thick, were prepared from undisturbed soil samples to study pedogenic features using a transmitted polarized light microscope (German Leitz model) with 40x magnification. Pedogenic phenomena, such as coatings, crystals, and aggregates, were examined following the methods outlined by studies [18, 19].

3. RESULT AND DISCUSSION

3.1 Particle size distribution of soil

It is observed that most of the samples classified as "Clay" (C) in Table 3 contain a very high percentage of clay. It was also noted that there is a variation in the percentages of sand, silt, and clay. The results showed a significant variation in the percentages of sand, silt, and clay among the different samples. This indicates a variation in soil properties between the different locations.

Effect of depth on soil texture: In some locations, soil texture varies with depth. For example, in the "Rashidiya (vegetables)" site, the soil texture changes from "Sandy Clay Loam" (SCL) in the surface layer to "Silty Clay" (SC) in the deeper layer [20].

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Table 3. Soil physical properties

Name	Depth, cm	Soil Separators, g/kg			Texture	Bulk Density, g/cm³
		Sand	Silt	Clay		
ZaP1d1	0 - 10	193	182.5	624.5	C	1.73
ZaP1d2	10 - 30	118	307.5	574.5	C	1.47
ZaP2d1	0 - 20	313	332.5	354.5	CL	1.56
ZaP2d2	20 - 45	338	257.5	404.5	C	1.79
ZaP3d1	0-15	155.5	515	329.5	C	1.51
ZaP3d2	15 - 45	113	417.5	469.5	SC	1.99
RaP1d1	0 - 10	188	407.5	404.5	SC	1.58
RaP1d2	10 - 35	163	382.5	454.5	C	1.60
RaP2d1	0 - 18	330.5	365	304.5	CL	1.39
RaP2d2	18 - 35	680.5	15	304.5	SCL	1.93
RaP3d1	0 - 13	298	407.5	294.5	CL	1.82
RaP3d2	13 - 40	273	407.5	319.5	CL	1.42
BaP1d1	0 - 12	905	367.5	542	C	1.84
BaP1d2	12- 47	115.5	267.5	617	C	1.67
BaP2d1	0 - 15	105.5	415	479.5	SC	1.81
BaP2d2	15 - 45	88	292.5	619.5	C	1.91
BaP3d1	0 - 13	63	292.5	644.5	C	1.83
BaP3d2	13 - 26	88	292.5	619.5	C	1.58
ZawP1d1	0 – 20	305.5	292.5	402	C	1.69
ZawP1d2	20 - 42	330.5	242.5	427	C	1.71
ZawP2d1	0 - 17	165.5	282.5	552	C	1.65
ZawP2d2	17 - 48	138	285	577	C	1.65
ZawP3d1	0 - 18	215.5	257.5	527	C	1.73
ZawP3d2	18 - 41	190.5	232.5	577	C	1.82

Regarding the effect of depth on soil texture, the texture varies with depth. For example, in the "Rashidiya (vegetables)" site, the soil texture changes from SCL in the surface layer to SC in the deeper layer.

Table 4 also shows that the best weathering indicator is the CIW index, as it reflects the depletion of soluble elements and the increase in the concentration of fixed aluminum. The results showed that samples RaP3d1 and RaP3d2 recorded the highest CIW values and the lowest WR values, indicating the highest degree of chemical weathering. Therefore, CIW is the best indicator of weathering among the samples.

Samples with low bulk density values (1.39–1.58 g/cm³), such as RaP2d1 and ZaP1d2, were characterized by higher clay and silt contents. This implies a greater fine porosity and a higher capacity for water retention, which creates favorable conditions for chemical weathering. The prolonged residence time of water in such soils enhances the interaction between minerals and soil solutions, leading to the decomposition of primary minerals—particularly feldspars and ferromagnesian minerals—and the formation of secondary clay minerals such as illite and smectite. Therefore, low bulk density may be considered an indicator of advanced soil development and relative stability under long-term weathering. Conversely, samples with high bulk density values (1.8–1.99 g/cm³), including BaP2d1 and RaP2d2, contained higher sand proportions, which reflect lower porosity and greater particle packing. These conditions restrict water and air movement within the soil, thereby limiting chemical reactions and favoring physical weathering processes such as thermal expansion and contraction, and mechanical disintegration of rock fragments. The limited residence time of water in these soils reduces the potential for chemical alteration. A clear inverse relationship was observed between bulk density and the clay–silt fraction, where increasing fine particles decreased density, enhanced soil porosity, and promoted chemical weathering. In contrast, higher bulk density associated with sandy textures or structural compaction reduced the rate of chemical weathering and emphasized the role of mechanical processes as the dominant mechanism of parent material breakdown. Overall, the results indicate that bulk density serves as an effective indicator of soil development and weathering intensity, reflecting the balance between physical and chemical processes in arid and semi-arid environments. Lower bulk density values denote well-developed soils that have undergone effective chemical weathering, while higher values correspond to relatively young soils dominated by rapid but shallow physical disintegration.

Soils with finer textures and lower bulk densities (e.g., Rashidiya (Inceptisols)) exhibited higher CIW values, indicating more advanced chemical weathering due to prolonged water retention. In contrast, coarse-textured soils in Zummar and Zawita showed lower CIW values, suggesting dominance of physical weathering under drier conditions.

3.2 Weathering indices analysis

The results in Table 4 showed a clear variation in the values of element oxides between the pedons of the four sites. The results showed a decrease and convergence in Na_2O values in most of the studied sites, as the values ranged from 0.042% to 0.052%, and the highest value was in (RaP2d1). While there was an increase in silicon oxide values for most samples, ranging between 30.59% and 47.32% and the highest value was in the (RaP3d2) area.

Table 4. Percentage of major and minor element oxides in 53 - 100 µm for the studied pedons using the XRF device

Name of Pedon	Al_2O_3 %	CaO %	Na_2O %	MgO %	Fe_2O_3 %	TiO_2 %	SiO_2 %
ZaP1d1	5.66	24.94	0.045	2.45	3.94	0.46	35.61
ZaP1d2	5.71	23.51	0.042	2.36	4.09	0.47	35.45
ZaP2d1	5.89	22.55	0.048	2.62	4.22	0.54	38.98
ZaP2d2	5.69	20.98	0.050	2.51	4.05	0.51	37.22
ZaP3d1	7.49	17.07	0.042	3.13	5.00	0.63	33.53
ZaP3d2	7.71	16.99	0.045	3.33	5.05	0.62	43.63
RaP1d1	7.40	13.66	0.046	4.14	5.25	0.58	43.51
RaP1d2	7.70	13.69	0.048	4.34	5.45	0.58	44.24
RaP2d1	8.07	11.33	0.052	4.87	5.68	0.62	46.55
RaP2d2	8.05	11.49	0.051	5.08	5.71	0.66	46.23
RaP3d1	8.40	11.46	0.048	5.36	5.76	0.66	47.11
RaP3d2	8.32	11.44	0.049	4.97	5.83	0.647	47.32
BaP1d1	7.18	16.84	0.045	3.76	4.85	0.54	43.34
BaP1d2	7.66	16.94	0.047	3.67	5.20	0.56	43.39
BaP2d1	7.19	14.19	0.045	3.28	5.02	0.58	43.80
BaP2d2	7.31	16.27	0.045	3.32	5.23	0.57	42.02
BaP3d1	7.21	17.09	0.046	3.25	5.06	0.56	41.69
BaP3d2	8.70	17.84	0.043	4.27	5.18	0.62	47.84
ZawP1d1	6.50	17.63	0.050	1.84	4.03	0.56	41.74
ZawP1d2	6.473	18.63	0.045	1.78	3.86	0.53	40.09
ZawP2d1	5.441	26.24	0.047	1.75	3.78	0.42	34.33
ZawP2d2	4.54	27.62	0.046	1.51	3.63	0.39	30.59
ZawP3d1	7.76	13.59	0.044	2.16	4.85	0.60	44.29
ZawP3d2	7.99	14.52	0.045	2.15	5.15	0.60	44.27

The results presented in Table 5 indicate that the samples from positions 9 to 12 in the Al-Rashidiya region (RaP2d1, RaP2d2, RaP3d1, and RaP3d2) exhibit a high weathering ratio. This suggests that these samples have undergone a significant degree of weathering, resulting in a marked loss of calcium and sodium relative to aluminum. In contrast, samples from pedon one in the Zumar region, as well as samples from positions 19 to 24 in the Zawita region, show a relatively low Chemical Index of Weathering. These findings indicate that these samples experienced less weathering, retaining higher concentrations of calcium and sodium compared to aluminum.

Table 5 reveals a significant variation in WR values among the different samples. This indicates that the soils in the area have experienced varying degrees of weathering.

High Weathering Samples: Samples (22) taken from the Zawita region (ZawP2d2) showed very high WR. This could be due to factors such as heavy rainfall or acidic soils.

Low Weathering Samples: Samples 9 to 12 from the Al-

Rashidiya region (RaP2d1, RaP2d2, RaP3d1, and RaP3d2) exhibited relatively low WR, indicating a lesser degree of weathering. A notable variation in the WR values was observed among the different samples, suggesting differing extents of weathering within this group. Samples from pedon Zamar and the Al-Rashidiya region (ZaP3d1, RaP1d2, RaP2d1, RaP2d2, RaP3d1, and RaP3d2) showed relatively low values for the weathering index (WI), indicating that these samples underwent a higher degree of weathering, resulting in significant losses of silica relative to aluminum and iron.

Table 5. Weathering index values for the study area

Name of Pedon	CIW	WR	WI	Si/Ses
ZaP1d1	0.184	58.90	6.010	3.706
ZaP1d2	0.195	54.14	5.732	3.615
ZaP2d1	0.206	46.33	5.775	3.856
ZaP2d2	0.213	46.12	5.669	3.815
ZaP3d1	0.304	32.14	3.852	2.682
ZaP3d2	0.311	32.67	4.525	3.416
RaP1d1	0.350	30.54	4.316	3.437
RaP1d2	0.359	30.75	4.212	3.360
RaP2d1	0.415	25.99	4.024	3.383
RaP2d2	0.410	25.15	4.001	3.359
RaP3d1	0.422	25.53	3.951	3.326
RaP3d2	0.420	25.45	3.969	3.342
BaP1d1	0.298	38.05	4.783	3.600
BaP1d2	0.310	36.43	4.493	3.374
BaP2d1	0.335	30.11	4.532	3.586
BaP2d2	0.309	33.97	4.441	3.348
BaP3d1	0.296	35.84	4.576	3.396
BaP3d2	0.327	35.21	4.524	3.444
ZawP1d1	0.269	34.47	5.346	3.960
ZawP1d2	0.257	38.48	5.403	3.879
ZawP2d1	0.171	65.33	6.276	3.723
ZawP2d2	0.141	73.10	6.789	3.742
ZawP3d1	0.363	26.20	4.377	3.510
ZawP3d2	0.354	27.65	4.274	3.367

3.3 Thin section preparation

The results in Figure 2 showed the presence of carbonates in the soil, indicating that these soils may be derived from calcareous sedimentary rocks or have been influenced by secondary carbonate formation processes. Carbonates affect soil properties such as pH and water retention capacity. Quartz was also observed in the soil, often indicating the presence of sand or siliceous rock materials. The presence of quartz affects soil texture and physical properties. Vugs were also observed, indicating the presence of pores in the soil. The size of the vugs shown in the figure is 0.3 mm, indicating the presence of small pores, as illustrated in the figure.

Figure 2. B horizon for the ZaP1d2 pedon

Figure 3 shows the presence of carbonates in the soil, indicating a calcareous sedimentary origin or the influence of secondary carbonate formation processes. Carbonates affect soil properties, including pH and water retention capacity. The chert in the soil indicates the presence of hard and weathering-resistant siliceous rock materials. Chert influences soil texture and water retention capacity. The clay in the soil affects its physical and chemical properties, such as water and nutrient retention capacity.

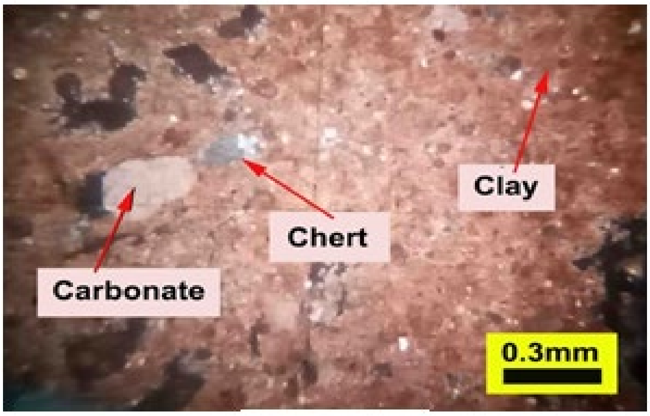

Figure 3. B horizon for the ZaP2d2 pedon

Figure 4 illustrates the presence of quartz, which often indicates the presence of sand or siliceous rock materials. The presence of quartz affects soil texture and physical properties. The presence of chert in the soil indicates the presence of hard, siliceous rock materials, which can affect soil texture and water retention capacity. Channel porosity indicates the presence of channels or pathways in the soil that allow for the movement of water and air. These channels can result from various factors, such as plant roots, animal activity, or weathering processes. The size of the channels shown in the figure is 0.3 mm, indicating the presence of small pores.

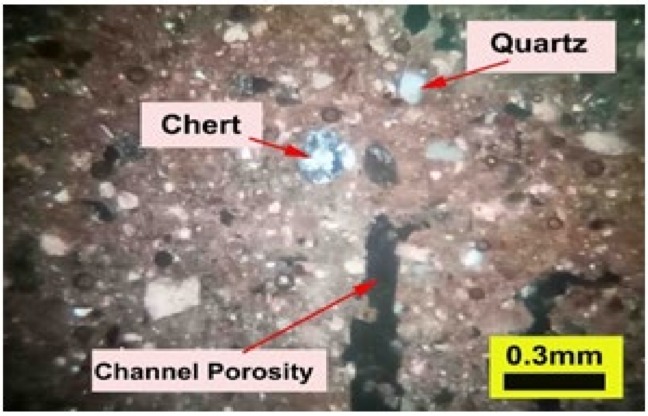

Figure 4. B horizon for the ZaP3d2 pedon

Figure 5. B horizon for the RaP1d2 pedon

Figure 6. B horizon for the RaP2d2 pedon

Figure 5 illustrates the presence of a clay body, indicating an accumulation or aggregation of clay minerals within the soil.

Figure 6 illustrates the presence of iron oxides, which significantly affect soil color and properties. Figure 7 illustrates the presence of a clay body and carbonates. These components significantly affect soil properties.

Figure 8 illustrates the presence of iron oxides and carbonates. The presence of iron oxides significantly affects soil color and properties. The presence of carbonates affects soil properties such as pH and water retention capacity. Figure 9 illustrates the presence of vugs and porosity. These vugs can result from various factors, such as: Mineral dissolution: Some minerals, such as carbonates, can dissolve due to acidic water, leaving vugs in the soil. Organic matter decomposition: The decomposition of plant roots or other organic matter can leave vugs in the soil. Rock fracturing: The fracturing of rocks due to weathering processes can create vugs in the soil.

Figure 7. B horizon for the RaP3d2 pedon

Figure 8. B horizon for the BaP1d2 pedon

Figure 9. B horizon for the BaP2d2 pedon

Figure 10 illustrates that the presence of organic matter significantly affects soil properties. Figure 11 illustrates the presence of quartz and vugs. The presence of quartz affects soil texture and physical properties. Vugs can result from various factors, such as: Mineral dissolution: Some minerals, like carbonates, can dissolve due to acidic water, leaving vugs in the soil. Organic matter decomposition: The decomposition of plant roots or other organic matter can leave vugs in the soil. Rock fracturing: The fracturing of rocks due to weathering processes can create vugs in the soil.

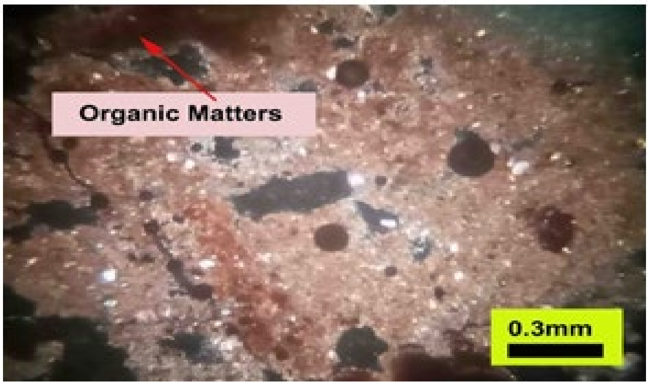

Figure 10. B horizon for the BaP3d2 pedon

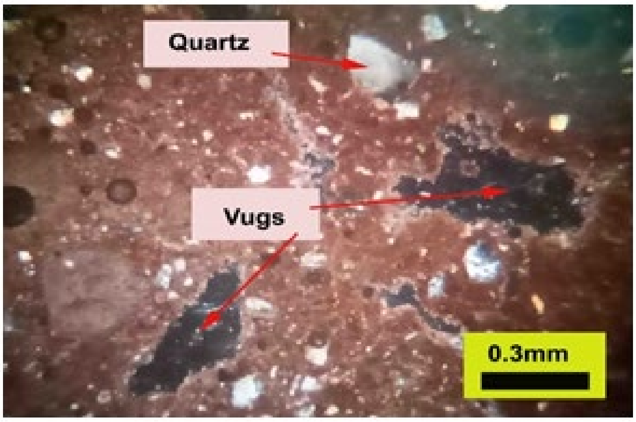

Figure 11. B horizon for the ZawP1d2

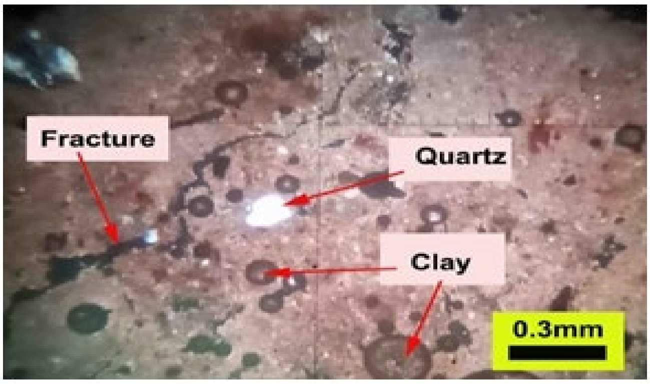

Figure 12. B horizon for the ZawP2d2

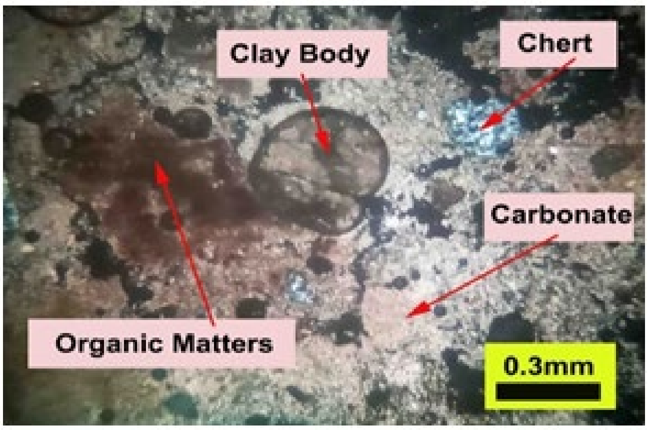

Figure 13. B horizon for the ZawP3d2

Figure 12 illustrates the presence of fractures within the soil. These fractures can arise from a variety of factors, including Soil Shrinkage and Expansion: Fluctuations in moisture and temperature levels induce soil shrinkage and expansion, leading to the development of fractures. Ground Movements: Seismic activity or landslides can cause fractures to form within the soil structure. Rock Weathering: The breakdown of rocks through weathering processes can create fractures that propagate into the overlying soil. Presence of Quartz: The presence of quartz significantly influences soil texture and its physical properties. Presence of Clay: Clay content plays a crucial role in determining the soil's physical and chemical characteristics, such as water and nutrient retention capacity.

Figure 13 illustrates the presence of a clay body, which significantly influences soil properties. Chert affects soil texture and its water retention capacity. Carbonates influence soil characteristics such as pH and water retention capacity. Organic matter also significantly impacts soil properties.

The presence of clay coatings and iron oxides in Rashidiya samples corresponds with higher CIW values, confirming intensive leaching and secondary clay formation. Meanwhile, the dominance of carbonate nodules in Zummar and Zawita restricts leaching and indicates weaker chemical alteration. These micromorphological observations are consistent with the chemical data and help explain variations in weathering intensity among the studied soil orders.

The presence of carbon nodules, shown in Figures 2, 3, 7, 8, 13, often leads to a decrease in the filtration rate due to clogging of pores and increased hardening. It also causes inhomogeneity in the movement of water and moisture within the soil, and ultimately affects irrigation efficiency, nutrient distribution, and root growth.

The higher weathering degree observed in Rashidiya (Inceptisols) can be attributed to its relatively higher rainfall and finer parent materials, which enhance chemical alteration. Similar patterns were reported by Harnois [14] and Darmody et al. [16], indicating that CIW is a reliable indicator of prolonged leaching in semi-humid regions.

The CIW index performed best among all tested indicators, showing clear differentiation between soil orders.

Micromorphological features such as clay coatings and iron oxide accumulations were closely related to higher CIW values, indicating advanced pedogenic development. Conversely, carbonate nodules and high bulk density limited chemical weathering, promoting physical disintegration instead.

4. CONCLUSIONS

This study evaluated the weathering intensity and micromorphological variations among four major soil orders in northern Iraq. Results demonstrated that both climate and parent material strongly control the degree of chemical alteration. The findings of this study demonstrate that soil sustainability and the intensity of weathering processes in northern Iraq are strongly influenced by land use type, soil order, and micromorphological development. The comparative assessment among the four sites—Zummar, Rashidiya, Ba'shiqah, and Zawita—revealed that variations in agricultural practices significantly alter soil physical and chemical properties, thereby modifying its micromorphological features and degree of weathering. The Rashidiya soils, representing the Inceptisol order, exhibited the highest chemical weathering intensity, as evidenced by elevated CIW values and a corresponding decrease in the WR, indicating substantial leaching of basic cations and enrichment in aluminum oxides. Conversely, the soils of Zummar and Zawita showed relatively lower degrees of chemical alteration, reflecting the dominance of physical weathering processes under semi-arid climatic conditions.

Micromorphological observations further supported these findings, revealing the widespread presence of carbonate nodules, quartz grains, clay coatings, and iron oxides, all of which serve as indicators of the pedogenic processes governing soil development. The occurrence of fine pores and vughs in the microstructure suggests enhanced internal drainage and localized zones of dissolution, which are closely associated with chemical weathering pathways. In contrast, compacted horizons characterized by higher bulk density values exhibited reduced porosity and water movement, conditions that favor physical disintegration rather than chemical alteration.

Overall, the integration of micromorphological and geochemical data confirmed that the CIW is the most effective and reliable indicator for assessing the degree of soil weathering under diverse land use conditions. Agricultural activities, particularly continuous vegetable and wheat cultivation, accelerate soil transformation through increased moisture fluctuation and organic inputs, leading to moderate but progressive chemical weathering. The results highlight the importance of adopting sustainable land management practices that preserve soil structure, minimize carbonate accumulation, and maintain balanced weathering processes to ensure long-term soil fertility and environmental stability in northern Iraq.

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