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EMPLOYING SOIL GEOCHEMISTRY TO PROMOTE SUSTAINABLE DEVELOPMENT: A CASE STUDY OF THE WADI AL KHALI AND WADI AL HAMIM AREAS, NE LIBYA

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استخدام علم جيوكيمياء التربة لتعزيز التنمية المستدامة: دراسة حالة لمنطقتي وادي الخالي ووادي الحميم، شمال شرق ليبيا

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Abstract

A geochemical evaluation of Holocene soil was conducted in the Wadi Al Khali and Wadi Al Hamim areas in order to link soil geochemistry to sustainable development in Libya. The CaO content indicated that the studied samples belonged to the calcareous soil category. The source area appears to have experienced slight to high weathering, as indicated by the CIA, CIW, RR, and PIA values. The dominance of semi-arid to semi-humid conditions is supported by the K_2O/Al_2O_3, CIA, and T values. The soil consists of immature sediments and has low paleoproductivity. The depositional environment was suboxic marine as shown by the Ca, Ca+Fe, MgO, Fe_2O_3, Fe/Al, Ca/(Ca+Fe) and Al/(Al+Fe) values. Based on the Ca/Mg, K/Mg, P/S, K/Na, and Fe/Mn ratios, the soil can be categorized as marginally suitable (category S3).

Keywords: Agricultural Suitability, Soil Geochemistry, Sustainable Development, Libya.

الملخص

أُجري تقييم جيوكيميائي لتربة الهولوسين في منطقتي وادي الخالي ووادي الحميم بهدف ربط جيوكيمياء التربة بالتنمية المستدامة في ليبيا. أشارت نسبة أكسيد الكالسيوم (CaO) إلى أن العينات المدروسة تنتمي إلى فئة التربة الكلسية. ويبدو أن منطقة المصدر قد تعرضت لتجوية تتراوح بين الخفيفة والشديدة، كما يتضح من قيم CIA وCIW وRR وPIA. وتؤكد قيم K_2O/Al_2O_3 وCIA وT غلبة الظروف شبه الجافة إلى شبه الرطبة. تتكون التربة من رواسب غير ناضجة وتتميز بانخفاض إنتاجيتها القديمة. كانت بيئة الترسيب بحرية شبه مؤكسدة، كما يتضح من قيم Ca وCa+Fe وMgO وFe_2O_3 وFe/Al و Ca/(Ca+Fe) وAl/(Al+Fe). وبناءً على نسب Ca/Mg وK/Mg وP/S وK/Na وFe/Mn، يمكن تصنيف التربة على أنها مناسبة للزراعة بشكل هامشي (الفئة S3).

الكلمات الدالة: الملاءمة الزراعية، جيوكيمياء التربة، التنمية المستدامة، ليبيا.

1. Introduction

Soil geochemistry is essential for applications such as mineral exploration (e.g., Dönmez, 2023), environmental monitoring (e.g., Mazhari et al., 2018), agriculture (e.g., Jayawardana et al., 2014), and climate change (e.g., Wu et al., 2025), because it investigates the chemical composition and processes within soil, looking at how elements, minerals, and organic matter interact to influence nutrient cycles, contaminant behavior, and ecosystem health. Using methods to map anomalies for exploration or evaluate pollution hazards, it examines elemental distributions and variations to comprehend soil genesis, evolution, and influences from natural and human sources. Soil geochemistry is essential to accomplishing the United Nations Sustainable Development Goals (e.g., Lal et al., 2021).

Preceding studies on Libyan soils have focused on classification (Elaalem et al., 2021), agricultural suitability (Nwer et al., 2020), salinity (Binmiskeen and Bohajar, 2025), degradation (El-Asswad and Abufaied, 1994; Abagandura et al., 2017; Nwer et al., 2021a), physicochemical characteristics (**El-Amamy et al., 1982;** Nassar et al., 2006; Masoud et al., 2024; Mohamed et al., 2025), vegetation distribution (Zurqani and Ben Mahmoud, 2021), fertilizer (El-Ghawi et al., 2005; Abubaker et al., 2020), agricultural production (Nwer et al., 2021b), mineralogy (Younis et al., 1999; Atkinson and Waugh, 2007), microbiology (Ferjani et al., 2021), engineering performance (Fookes and Gahir, 1995), and environmental pollution (Shenber and Eriksson, 1993; El-Ghawi et al., 2007; Voegborlo and Chirgawi, 2007; Elbagermi et al., 2013; Hesnawi and Mogadami, 2013; Saad et al., 2013, Maryol and Lin, 2015; Koshlaf et al., 2016; Mansur et al., 2016; Alatresh, 2023; Al Bosta et al., 2025; Feraj and Hasan, 2025; Hamed and Najem, 2025).

Linking soil geochemistry to sustainable development in Libya is the goal of this study. A geochemical assessment of Holocene soil was carried out in the northeastern Libyan areas of Wadi Al Khali and Wadi Al Hamim (Fig. 1) in order to accomplish this goal. The studied soil was derived primarily from limestone ranging in age from Miocene to Pleistocene (Carmignani, 1984; Giammarino, 1984).

2. Methodology

The mineralogical and chemical data of seventeen soil samples from Carmignani (1984) and Giammarino (1984) were utilized by the authors. The analyzed oxides included SiO_2, TiO_2, Al_2O_3, Fe_2O_3, MnO, MgO, CaO, Na_2O, K_2O, SO_3, P_2O_5, CO_2, and Cl. For statistical treatment, the SPSS© software was utilized. The equations employed in this investigation are displayed in Table 1. Table 2 displays how the parameters are interpreted.

3. Results and Discussion

3.1. Classification

The mineralogical and chemical data of the studied soil are shown in Tables 3 and 4. Calcareous soil has a high pH (alkaline) because of its high $CaCO_3$ content, which is frequently over 15% (CaO>8.43%). It also affects the availability of nutrients, particularly P, Fe, and Zn, which causes shortages in plants (lime-induced chlorosis). These soils, which are common in dry and semi-arid areas, can create hard layers (caliche), limit the circulation of water and roots, and have little organic matter. The examined soil is of the calcareous type, as indicated by the CaO values (18.03-42.04%, Table 4).

3.2. Statistical Treatment

3.2.1. Correlation Matrix

The examined oxides exhibit various correlations (Table 5). The following is a brief discussion of these correlations:

(1) Since SiO_2 and Al_2O_3 are essential components of silicate minerals, it is typical for them to have a positive correlation (r = 0.72). Clastic input or ongoing weathering are frequently the cause of this correlation.

(2) Al_2O_3 exhibits positive correlations with Fe_2O_3, TiO_2, and K_2O (r = 0.97, 0.91, and 0.97, respectively), reflecting their immobility during weathering and their shared interaction with iron oxyhydroxides and clay minerals. Despite the predominant $CaCO_3$ presence in calcareous soils, these oxides frequently serve as indications of the terrigenous clastic origin.

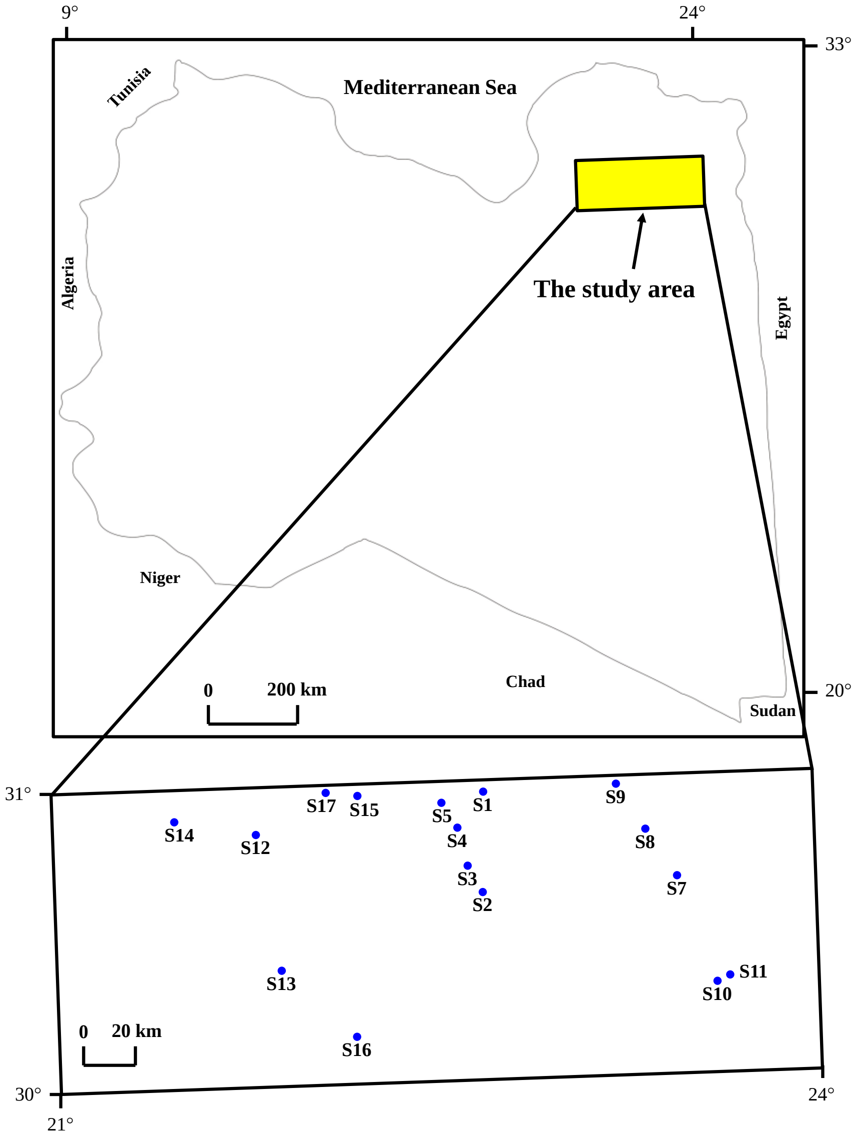

Figure 1: Composite map showing the location of the study area and the location of the samples (modified after Carmignani, 1984; Giammarino, 1984).

Table 1: Equations utilized to calculate the parameters.

Parameters	Equation
FeO (wt%)	$FeO = 0.8998*Fe_2O_3$
CaO in the silicate fraction (wt%)	If $Na_2O>CaO-P_2O_5$, then $CaO^* = CaO-P_2O_5$, while if $Na_2O<CaO-P_2O_5$, then $CaO^* = Na_2O$
Chemical index of alteration (wt%)	$CIA = (Al_2O_3/(Al_2O_3+CaO^*+Na_2O+K_2O))100$
Chemical index of weathering (wt%)	$CIW = (Al_2O_3/(Al_2O_3+CaO^*+Na_2O))100$
Ruxton ratio	$RR = SiO_2/Al_2O_3$
Plagioclase index of alteration (wt%)	$PIA = ((Al_2O_3-K_2O)/((Al_2O_3-K_2O)+CaO^*+Na_2O))100$
Temperature (°C)	$T = 0.56 \times CIA-25.7$
Index of compositional variability	$ICV = (Fe_2O_3+K_2O+Na_2O+CaO^*+MgO+MnO+TiO_2)/Al_2O_3$

Table 2: Interpretation of the parameters.

Parameter	Values	Interpretation	Reference
Ca/(Ca+Fe)	<0.4	Fresh water	Khan et al. (2023)
	0.4-0.8	Brackish water	
	0.8	Saline water	
Al/(Al+Fe)	<0.4	Marine origin	Liu et al. (2015)
	>0.4	Terrestrial origin	
Fe/Al	<0.5	Oxic conditions	Lyons and Severmann (2006)
	>0.5-0.6	Anoxic conditions	
P/Al	Low	Low paleoproductivity	Canfield (1994)
	Medium	Medium paleoproductivity	
	High	High paleoproductivity	
P/Ti	<0.34	Low paleoproductivity	Yang et al. (2022)
	0.34-0.79	Medium paleoproductivity	
	>0.79	High paleoproductivity	
CIA (%)	90−100	Extremely weathered	Nesbitt and Young (1982)
	80−90	Highly weathered	
	70−80	Moderately weathered	
	60−70	Slightly weathered	
	50−60	Very slightly weathered	
RR	0−10	Highly weathered	Ruxton (1968)
	10−30	Moderately weathered	
	>30	Low weathered	
CIW (%)	>70	Highly weathered	Harnois (1988)
	40−70	Moderately weathered	
	0−40	Low weathered	
PIA (%)	High	Highly weathered	Fedo et al. (1995)
	Medium	Moderately weathered	
	Low	Low weathered	
ICV	>0.84	Immature sediments	Cox et al. (1995)
	<0.84	Mature sediments	
CIA (%)	<70%	Arid climate	Nesbitt and Young (1982)
	80−100%	Humid climate	
K_2O/Al_2O_3	>0.2	Arid climate	Roy and Roser (2013)
	<0.2	Humid climate	

Table 3: Mineralogical data (concentration in wt%) of the studied soil (after Carmignani, 1984; Giammarino, 1984).

Area	Sample No. in the sheets	Sample No. in this work	Calcite	Dolomite	Gypsum	Halite	Residue
Wadi Al Khali	21	S1	37.81	0.00	0.23	<1	61.69
	22	S2	36.92	0.00	0.38	-	62.70
	23	S3	35.95	0.00	0.19	<1	63.75
	26	S4	51.95	0.00	11.80	<1	35.89
	27	S5	52.05	0.00	17.25	-	30.70
	38	S6	36.08	1.86	0.50	2.45	59.11
	39	S7	41.36	0.00	1.88	2.62	54.14
	40	S8	30.84	0.00	0.65	<1	68.48
	41	S9	32.47	0.00	1.14	-	66.39
	59	S10	30.90	0.00	0.38	<1	67.79
	60	S11	25.74	0.00	0.25	<1	73.95
Wadi Al Hamim	57	S12	30.45	0.00	0.57	<1	68.92
	58	S13	32.74	0.00	0.16	<1	67.08
	59	S14	43.00	0.00	0.16	<1	56.83
	66	S15	34.51	3.73	0.24	1.81	59.71
	68	S16	28.09	0.00	0.14	<1	71.75
	69	S17	41.24	0.00	0.27	1.27	57.22

Table 4: Chemical analysis data (concentration in wt%) of the studied soil (after Carmignani, 1984; Giammarino, 1984).

Area	Sample No. in the sheets	Sample No. in this work	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO*	MnO	MgO
Wadi Al Khali	21	S1	38.97	0.55	10.19	3.65	3.28	0.17	4.18
	22	S2	40.85	0.64	7.87	3.08	2.77	0.06	3.45
	23	S3	44.21	0.42	7.00	2.70	2.43	0.05	3.17
	26	S4	17.64	0.13	2.41	0.96	0.86	0.03	1.70
	27	S5	18.12	0.02	2.05	0.88	0.79	0.02	1.73
	38	S6	36.49	0.53	10.67	3.98	3.58	0.07	4.91
	39	S7	34.24	0.39	7.37	2.82	2.54	0.05	3.68
	40	S8	43.63	0.59	10.42	4.03	3.63	0.07	3.94
	41	S9	44.12	0.35	9.36	4.25	3.82	0.09	3.89
	59	S10	45.13	0.44	7.87	2.85	2.56	0.05	3.49
	60	S11	48.27	0.50	8.88	3.00	2.7	0.06	4.42
Wadi Al Hamim	57	S12	40.45	0.73	13.26	5.95	5.35	0.07	4.66
	58	S13	39.18	0.64	12.13	4.94	4.45	0.06	3.95
	59	S14	33.93	0.49	9.07	3.53	3.18	0.05	3.49
	66	S15	38.88	0.52	10.43	3.49	3.14	0.06	4.72
	68	S16	43.72	0.63	12.71	4.84	4.36	0.06	5.16
	69	S17	37.13	0.43	8.49	3.07	2.76	0.05	3.93

Table 4: Continued.

Area	Sample No. in the sheets	Sample No. in this work	CaO	Na_2O	K_2O	P_2O_5	SO_3	CO_2	Cl
Wadi Al Khali	21	S1	23.10	0.44	1.61	0.13	0.16	16.64	0.17
	22	S2	26.34	0.15	0.94	0.09	0.15	16.24	-
	23	S3	24.81	0.19	1.29	0.10	0.13	15.82	0.07
	26	S4	42.00	0.13	0.40	0.02	7.96	22.86	0.22
	27	S5	42.04	0.11	0.35	0.10	8.00	22.89	-
	38	S6	20.94	2.13	1.73	0.13	0.34	16.77	1.49
	39	S7	27.29	1.62	1.17	0.09	1.27	18.20	1.59
	40	S8	21.09	0.18	1.69	0.13	0.44	13.57	0.02
	41	S9	21.14	0.09	1.55	0.11	0.48	14.28	-
	59	S10	23.29	0.95	1.38	0.12	0.26	13.60	0.57
	60	S11	21.44	0.23	1.49	0.11	0.17	11.33	0.04
Wadi Al Hamim	57	S12	18.03	0.14	2.48	0.17	0.38	13.40	0.04
	58	S13	22.11	0.10	2.09	0.12	0.10	14.41	0.01
	59	S14	28.59	0.09	1.48	0.10	0.10	18.92	0.01
	66	S15	20.54	1.54	1.58	0.14	0.16	16.97	1.10
	68	S16	18.10	0.02	2.08	0.13	0.09	12.36	0.02
	69	S17	25.46	0.88	1.39	0.10	0.18	18.15	0.77

Table 5: Correlation matrix of the examined oxides.

Oxides	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	SO_3	CO_2	Cl
SiO_2	1.00												
TiO_2	0.74	1.00											
Al_2O_3	0.72	0.91	1.00										
Fe_2O_3	0.65	0.86	0.97	1.00									
MnO	0.40	0.43	0.48	0.44	1.00								
MgO	0.73	0.82	0.92	0.82	0.46	1.00							
CaO	-0.90	-0.86	-0.93	-0.86	-0.48	-0.93	1.00						
Na_2O	-0.001	0.02	0.08	-0.04	0.01	0.33	-0.18	1.00					
K_2O	0.68	0.85	0.97	0.97	0.42	0.86	-0.89	0.03	1.00				
P_2O_5	0.59	0.67	0.80	0.77	0.42	0.76	-0.78	0.15	0.81	1.00			
SO_3	-0.90	-0.84	-0.82	-0.74	-0.46	-0.82	0.91	-0.19	-0.75	-0.62	1.00		
CO_2	-0.93	-0.75	-0.77	-0.73	-0.34	-0.75	0.89	0.11	-0.76	-0.64	0.77	1.00	
Cl	-0.21	-0.24	-0.14	-0.21	-0.12	0.17	0.01	0.97	-0.22	-0.03	-0.02	0.33	1.00

(3) Distinct mineral phases, chiefly calcite and silicate minerals, are suggested by the negative correlation between SiO_2 and CaO (r = −0.9).

(4) The absence of dolomite in the studied samples (except for samples S6 and S15, Table 3) explains the negative correlation between CaO and MgO (r = −0.93). Furthermore, MgO has positive correlations with SiO_2 and Al_2O_3, indicating that silicate minerals are the key MgO carriers in the studied samples.

(5) Due to prominent geochemical processes including the strong buildup of calcite and the fast mobility/leaching of Na_2O, SiO_2 and Al_2O_3 exhibit weak correlations with Na_2O (r = −0.001 and 0.08, respectively). The normal Si–Al–Na weathering interactions are disrupted by high Ca levels and fast Na_2O mobility, notwithstanding the relative stability of SiO_2 and Al_2O_3 (sesquioxides). Moreover, the presence of halite in most samples and the positive correlation between Na_2O and Cl (r = 0.97) indicate that halite is a significant Na_2O carrier.

(6) The presence of gypsum is the reason for the positive correlation between CaO and SO_3 (r = 0.91). Higher salinity (SO_3) levels are frequently associated with elevated CaO from $CaCO_3$ because both are increased by weathering or industrial contamination, which serves as a calcium source for sulfur compounds.

(7) Because $CaCO_3$ precipitates phosphorus as apatite (insoluble), there is a negative correlation between CaO and P_2O_5 (r = −0.78). Higher CaO levels frequently result in greater phosphate deficit despite potentially high total phosphorus content.

3.2.2. Principal Component Analysis

Three components (PC1, PC2, and PC3) were obtained from the principal component analysis (Table 6 and Fig. 2). Below is a condensed description of these components:

PC1: This component might be referred to as the clastic component because it shows positive loadings for SiO_2, TiO_2, Al_2O_3, Fe_2O_3, MgO, and K_2O. Positive loading is also observed for P_2O_5. For CaO, SO_3, and CO_2, negative loadings are noted.

PC2: Given that Na_2O and Cl exhibit positive loadings, this component can be designated as the halite component.

PC3: Due to the lack of loading, this component is essentially meaningless.

Table 6: Principal component analysis of the examined oxides.

Eigenvalues	8.43	2.20	1.03
% of Variance	64.83	16.89	7.92
Cumulative %	64.83	81.72	89.64
Principal components	PC1	PC2	PC3
SiO_2	0.79	-0.07	-0.54
TiO_2	0.97	-0.10	0.16
Al_2O_3	0.96	0.01	0.22
Fe_2O_3	0.90	-0.10	0.29
MnO	0.40	-0.01	0.53
MgO	0.89	0.32	0.04
CaO	-0.97	-0.14	0.14
Na_2O	-0.03	0.99	-0.02
K_2O	0.95	-0.09	0.18
P_2O_5	0.95	0.13	0.08
SO_3	-0.85	-0.18	0.24
CO_2	-0.82	0.23	0.43
Cl	-0.16	0.98	-0.01

3.2.3. Cluster Analysis

The studied samples were separated into three clusters by cluster analysis (Fig. 3). An explanation of these clusters is given below:

Cluster 1: Samples S4 and S5 made up this cluster. The samples have the highest concentrations of CaO, SO_3, and CO_2 and the lowest concentrations of SiO_2, TiO_2, Al_2O_3, Fe_2O_3, MgO, and K_2O.

Cluster 2: This cluster consisted of samples S2, S3, S7, S14, and S17. Compared to cluster 1, this cluster contains lower contents of CaO, SO_3, and CO_2, and higher contents of SiO_2, TiO_2, Al_2O_3, Fe_2O_3, MgO, and K_2O.

Cluster 3: This cluster included samples S1, S6, S8, S9, S10, S11, S12, S13, S15, and S16. The highest values of Al_2O_3 and K_2O and the lowest values of CaO are found in this cluster.

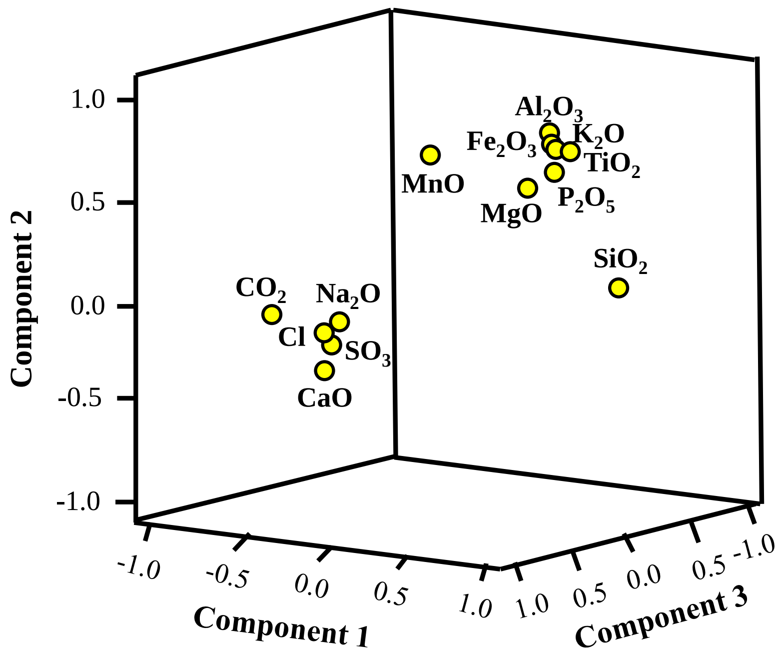

Figure 2: Plot of PC loadings of the examined oxides.

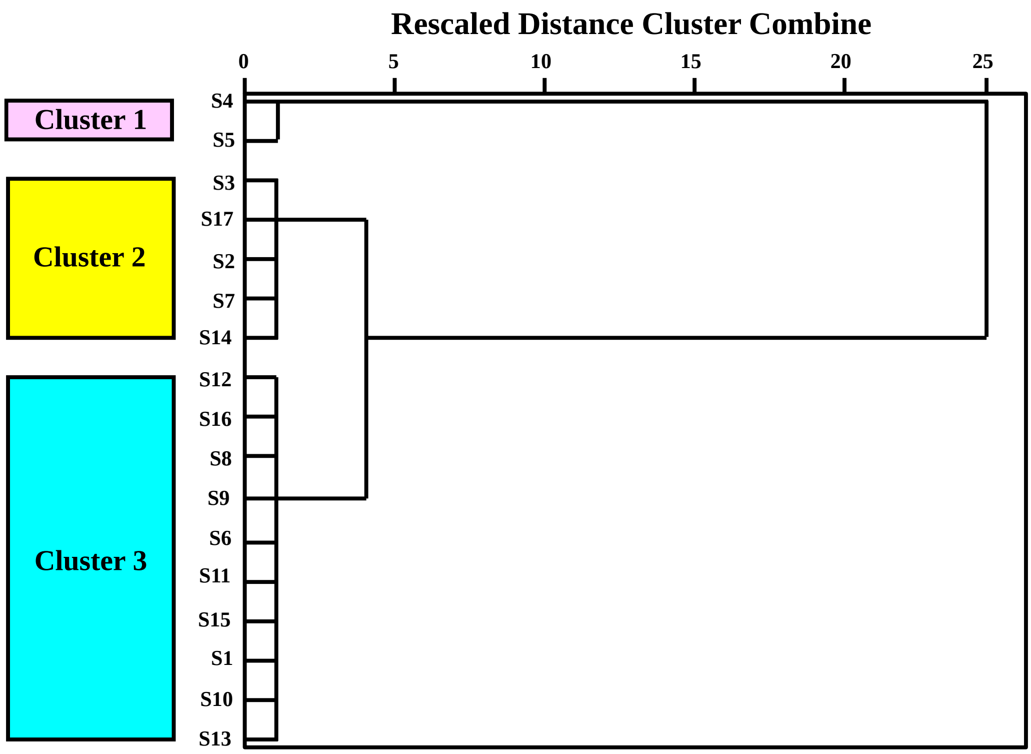

Figure 3: Dendrogram from cluster analysis (Ward method) of the studied samples.

3.3. Paleoweathering

The paleoweathering of the examined soil was evaluated using four parameters: RR, CIA, CIW, and PIA. The source area seems to have seen slight to high weathering, as illustrated in the diagrams of CIA versus CIW (Fig. 4), RR versus PIA (Fig. 5), and A-CN-K (Fig. 6).

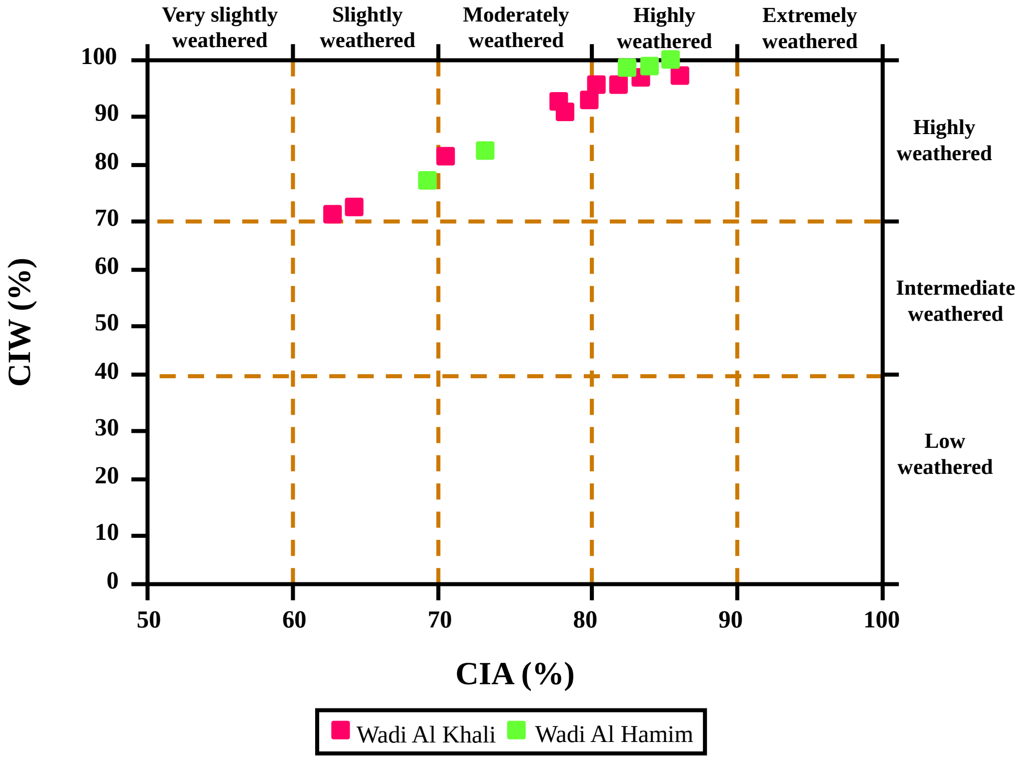

Figure 4: Binary plot of CIA vs. CIW showing the paleoweathering intensity in the source area (fields after Nesbitt and Young, 1982; Harnois, 1988).

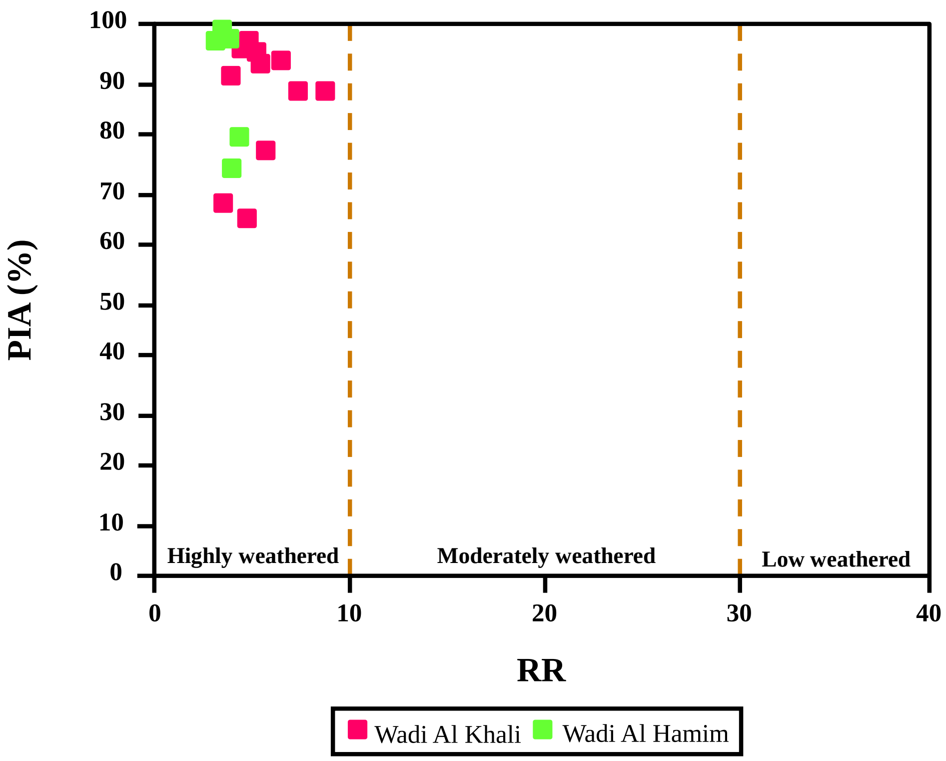

Figure 5: Binary plot of RR vs. PIA showing the paleoweathering intensity in the source area (fields after Ruxton, 1968; Fedo et al., 1995).

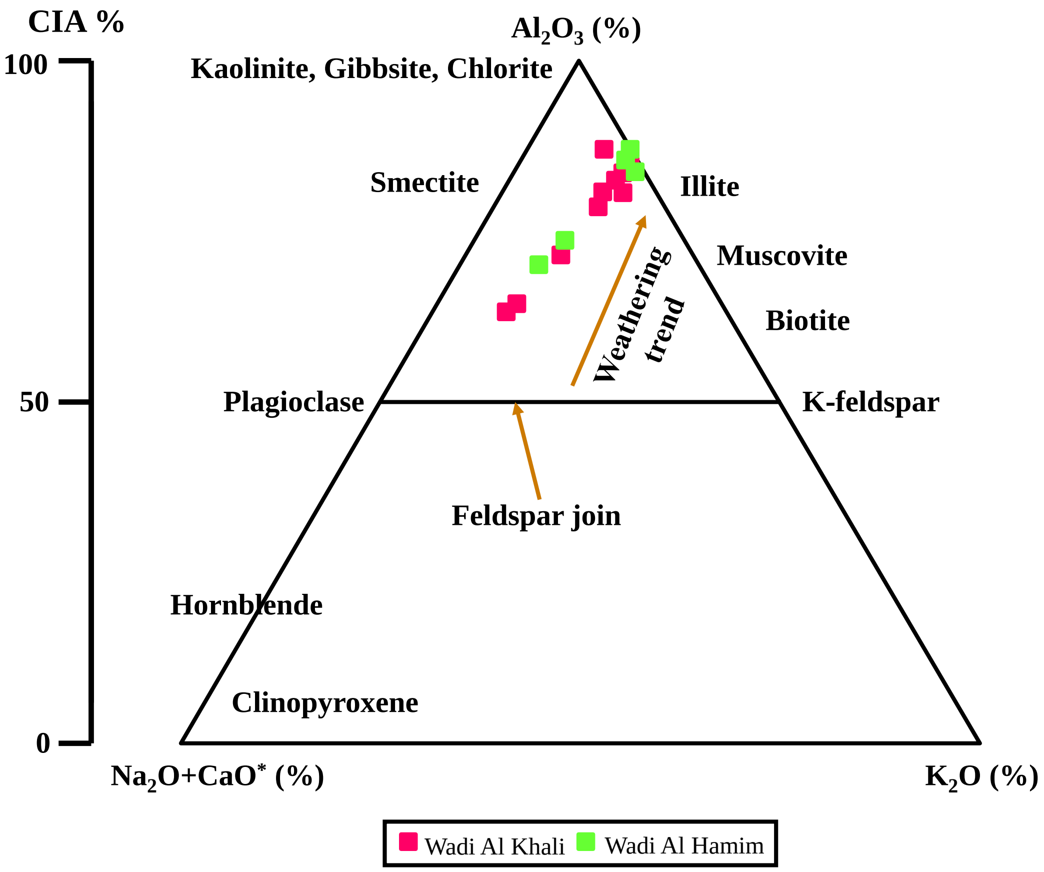

Figure 6: Ternary plot of Al_2O_3–(Na_2O+CaO*)–K_2O (A–CN–K) showing the paleoweathering intensity in the source area (fields after Nesbitt and Young, 1982).

3.4. Paleoclimate and Sediment Maturity

A number of parameters, including K_2O/Al_2O_3, CIA, and T, were employed to evaluate the paleoclimate. These parameters indicated that the temperature ranged from 20.64 to 34 °C in a semi-arid to semi-humid climate (Fig. 7). Moreover, there is a predominance of immature sediments, as demonstrated in Fig. 8.

3.5. Paleoproductivity

The paleoproductivity was assessed using the P/Al and P/Ti ratios. The examined samples exhibit low paleoproductivity, except for sample S5 in Wadi Al Khali, which show high paleoproductivity (Fig. 9).

3.6. Depositional Environment

The depositional environment was identified using several parameters, such as Ca, Ca+Fe, MgO, Fe_2O_3, Fe/Al, Ca/(Ca+Fe) and Al/(Al+Fe). The diagrams of MgO versus Fe_2O_3 (Fig. 10), Ca/(Ca+Fe) versus Al/(Al+Fe) (Fig. 11), and Ca versus Ca+Fe (Fig. 12) suggest that the deposition took place in a marine environment accompanied by obvious terrestrial input. Furthermore, the prevailing redox setting was suboxic, according to the Fe/Al ratio (0.44–0.6).

3.7. Suitability for Agriculture

Sait (2015a and b) suggested that the ratios of Ca/Mg, K/Mg, P/S, K/Na, and Fe/Mn in good soil should be 7, 1, 1, 4, and 2, respectively. Table 7 demonstrates that numerous ratios in the examined samples are much higher than the limits proposed by Sait (2015a and b). Therefore, the studied soil can be classified as marginally suitable (category S3) according to FAO (1976).

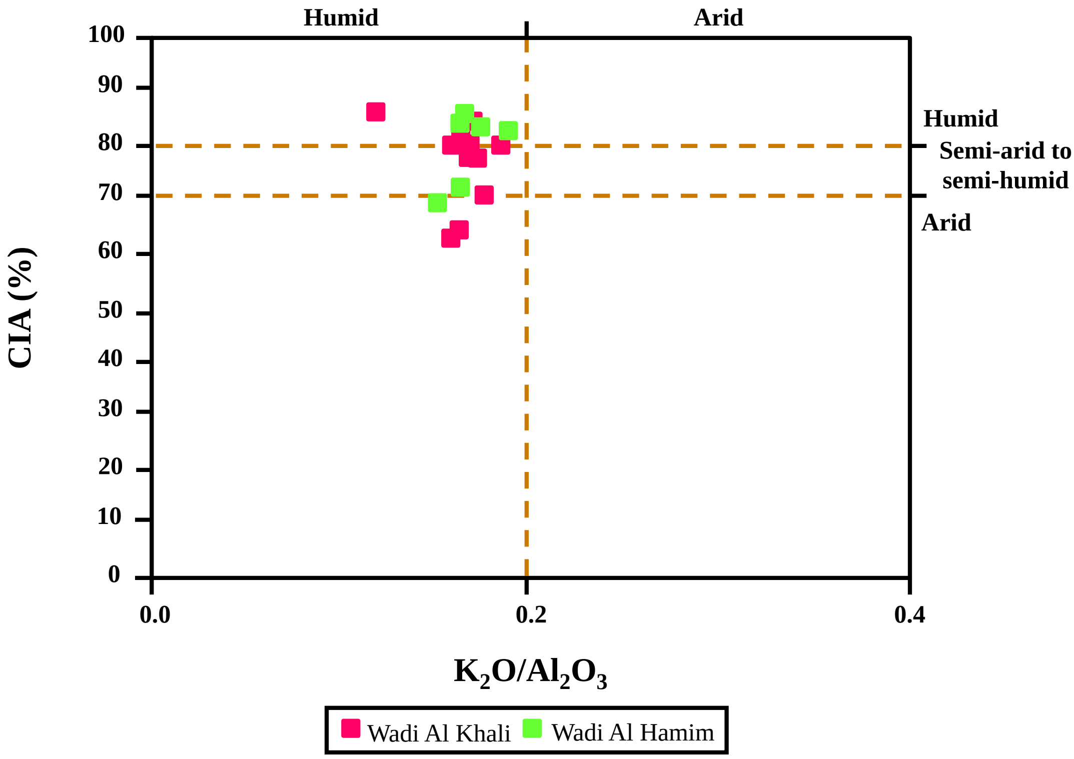

Figure 7: Binary plot of K_2O/Al_2O_3 vs. CIA showing the paleoclimate conditions during deposition of the studied soil (fields after Nesbitt and Young, 1982; Roy and Roser, 2013).

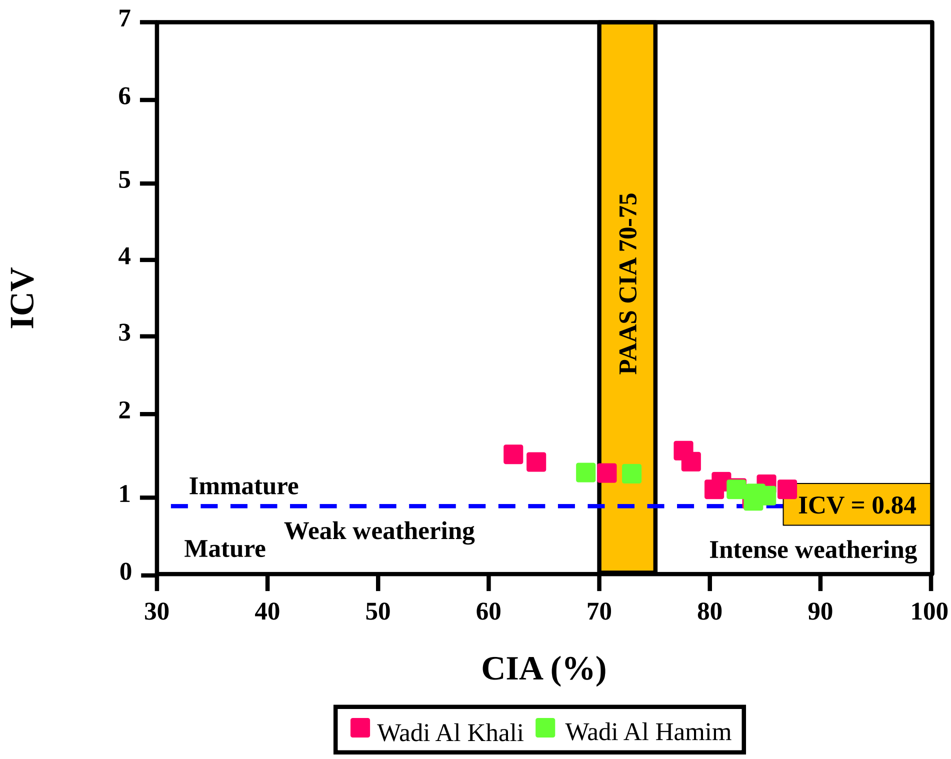

Figure 8: Binary plot of CIA vs. ICV showing the sediment maturity of the studied soil (fields after Nesbitt and Young, 1982; Cox et al., 1995).

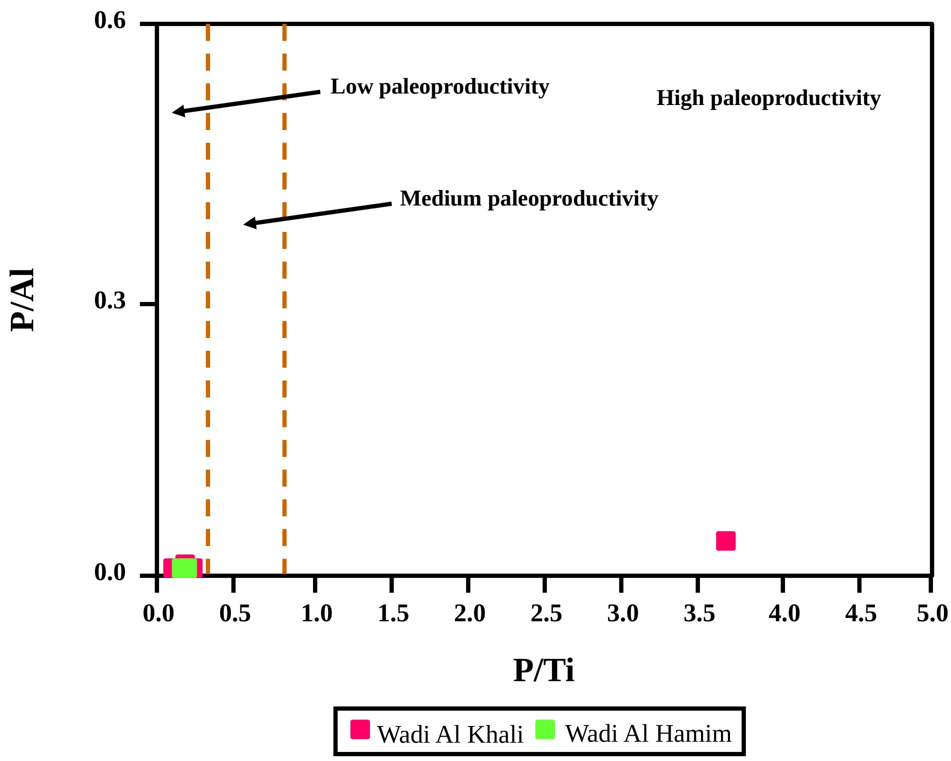

Figure 9: Binary plot of P/Ti vs. P/Al showing the paleoproductivity during deposition of the studied soil (fields after Canfield, 1994; Yang et al., 2022).

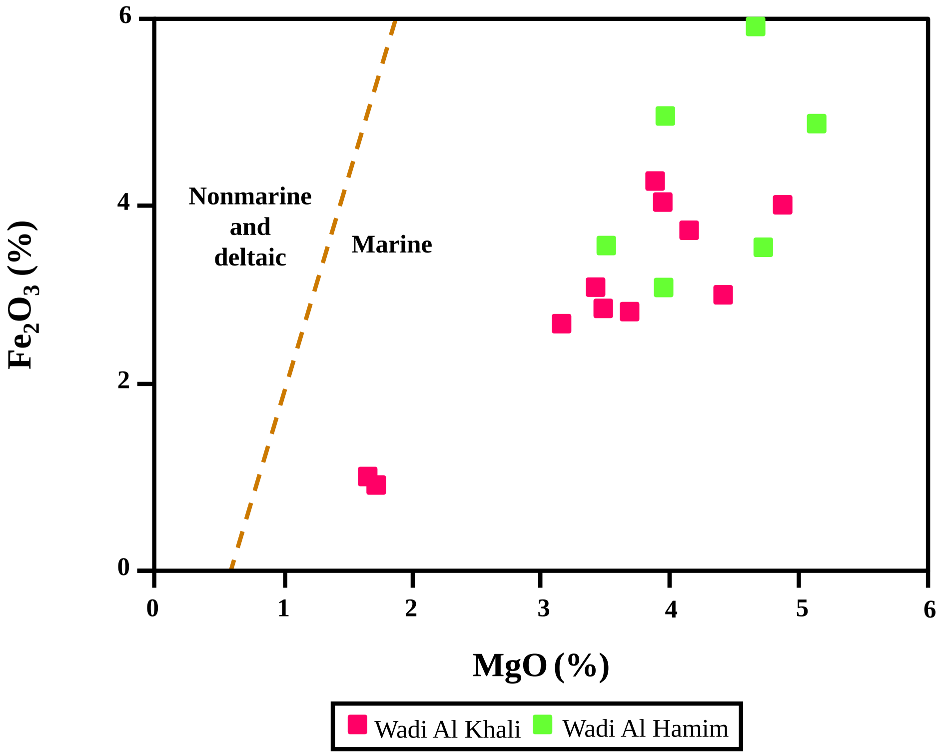

Figure 10: Binary plot of MgO vs. Fe_2O_3 showing the depositional environment of the studied soil (fields after Ratcliffe et al., 2007).

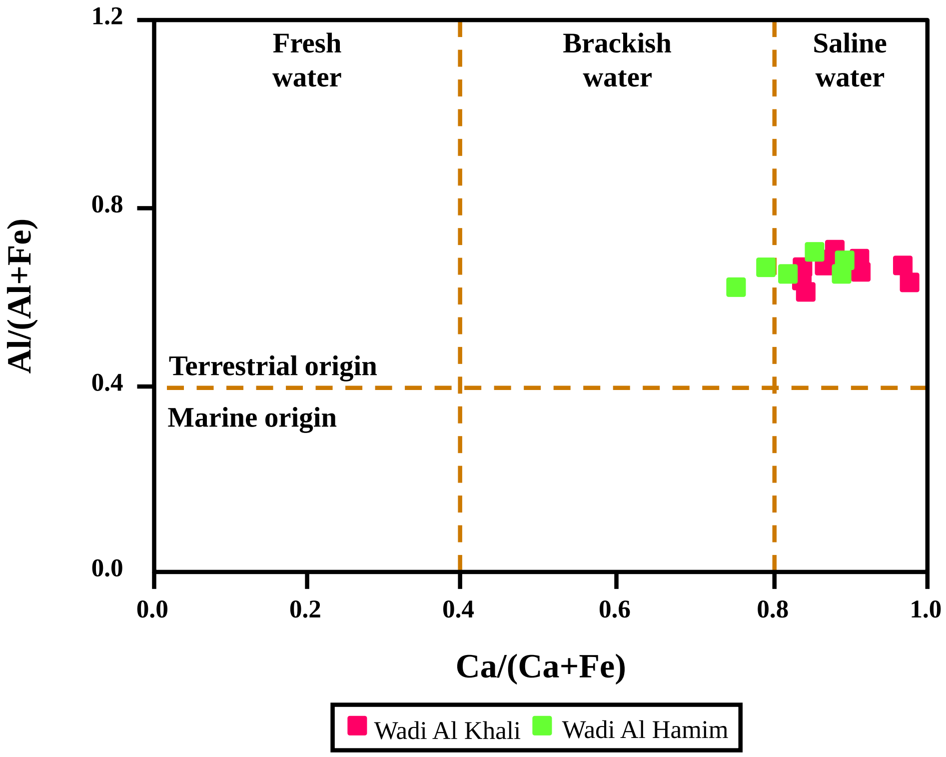

Figure 11: Binary plot of Ca/(Ca+Fe) vs. Al/(Al+Fe) showing the depositional environment of the studied soil (fields after Liu et al., 2015; Khan et al., 2023).

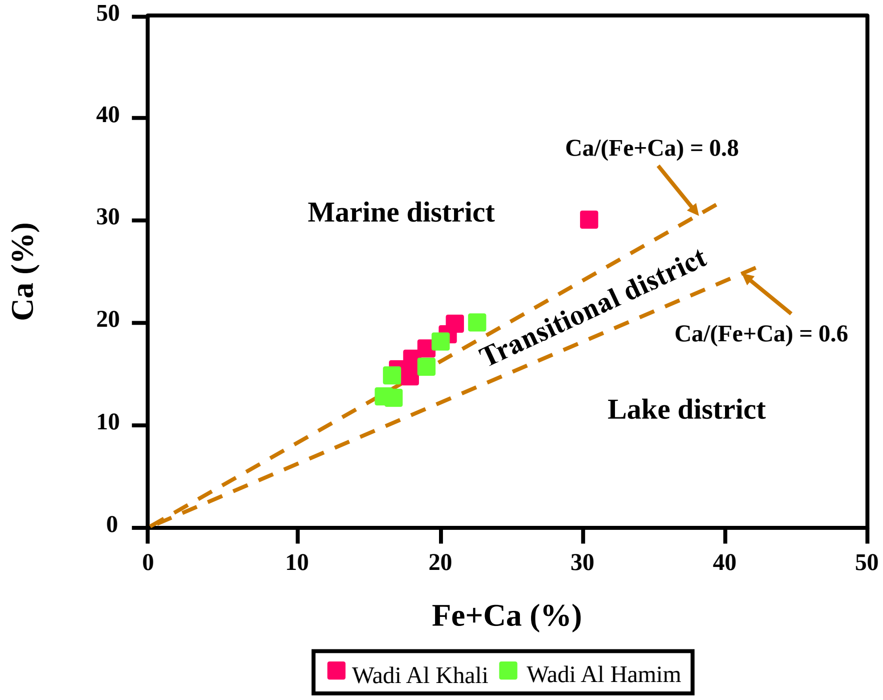

Figure 12: Binary plot of Fe+Ca vs. Ca showing the depositional environment of the studied soil (fields after He et al., 2019).

Table 7: Soil quality assessment ratios in the studied samples.

Area	Sample No. in the sheets	Sample No. in this work	Ca/Mg	K/Mg	P/S	K/Na	Fe/Mn
Wadi Al Khali	21	S1	6.54	0.53	0.89	4.10	19.52
	22	S2	9.03	0.38	0.66	7.03	46.67
	23	S3	9.26	0.56	0.85	7.62	49.09
	26	S4	29.24	0.33	0.00	3.45	29.09
	27	S5	28.76	0.28	0.01	3.57	40.00
	38	S6	5.05	0.49	0.42	0.91	51.69
	39	S7	8.78	0.44	0.08	0.81	51.27
	40	S8	6.33	0.59	0.33	10.53	52.34
	41	S9	6.43	0.55	0.25	19.32	42.93
	59	S10	7.90	0.55	0.51	1.63	51.82
	60	S11	5.74	0.47	0.71	7.27	45.45
Wadi Al Hamim	57	S12	4.58	0.74	0.49	19.87	77.27
	58	S13	6.62	0.73	1.32	23.44	74.85
	59	S14	9.69	0.59	1.10	18.44	64.18
	66	S15	5.15	0.46	0.96	1.15	52.88
	68	S16	4.15	0.56	1.59	116.65	73.33
	69	S17	7.67	0.49	0.61	1.77	55.82

4. Conclusions and Recommendation

By assessing the paleoweathering, paleoclimate, sediment maturity, paleoproductivity, depositional environment, and agricultural suitability, this study linked soil geochemistry of the Wadi Khali and Wadi Hamim areas to sustainable development in Libya. The key conclusions are as follows: (1) Calcareous soil is predominant in the study area; (2) The degree of paleoweathering obviously fluctuated; (3) The paleoclimate was primarily semi-arid to semi-humid; (4) The soil is essentially immature sediments; (5) In general, the deposition period was characterized by low paleoproductivity; (6) Suboxic conditions prevailed during soil deposition, which took place in a marine environment; and (7) Marginally suitable (category S3) is the confirmed soil category. Applying substantial, focused, and frequently costly changes to land with severe restrictions in order to make it viable for particular, frequently restricted crop uses is the main goal of marginally appropriate soil management. Key solutions include rigorous soil-improving practices including erosion control, deep fertilization, and precision irrigation to overcome physical or chemical restrictions.

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