Utilizing Soil Quality Index to Inform and Shape Agricultural Sustainability Strategies in Nineveh Governorate, Iraq

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Abstract

This research establishes a precision framework for assessing soil quality in the semi-arid regions of northern Nineveh, Iraq, by moving from the traditional Soil Quality Index (SQI) model to the modified soil quality (SQI-plus) model. While traditional soil quality indicators often produce overly optimistic "high quality" classifications, the SQI-plus model reveals the reality on the ground: significant quality degradation, placing most sites in the "medium quality" and "poor quality" classifications. This was achieved through the analysis of 40 geographically referenced sites using 11 physical, chemical, and morphological indicators: organic matter (OM), pH, cation exchange capacity (CEC), calcium carbonate ($CaCO_3$), electrical conductivity (EC), texture, bulk density (BD), effective depth, drainage, slope, and vegetation cover (VC). The study revealed that the decline in soil quality was primarily driven by limited organic matter (affecting 92.5% of sites) and high $CaCO_3$ content (85%), followed by lack of vegetation cover (62.5%) and increased bulk density (60%). The findings conclude that the SQI-plus model provides a symbolic system that identifies the specific factors for each site in arid and semi-arid environments. This work offers a transformative tool for sustainable land management, demonstrating that the resilience of agriculture in northern Iraq depends on addressing chemical and biological constraints rather than physical landscape parameters alone, providing a solid foundation for well-considered agricultural sustainability strategies.

Keywords: Soil Quality Index, agricultural sustainability, organic matter, SQI-plus, limiting factors

Introduction

Agricultural soil is essential for crop production and global food security (Tahat, et al., 2020; Veerman, et al., 2020). It provides 98.8% of our food (Kopittke, et al., 2021), creates the necessary environment for plant growth, and supports vital ecosystem processes (Samaniego, et al., 2025). Furthermore, soil quality is a key factor in determining land productivity, resulting from the interaction between intrinsic soil properties and dynamic

environmental processes, including climate, management practices, and biological activity (Bünemann, et al., 2018; Al-Naser, 2019; Józefowska, et al., 2026). Within this framework, soil quality serves as an integrative assessment approach that defines the capacity of a specific land unit to support particular uses (Freshteh, et al., 2024). The concept of soil quality evolved into an operational framework that can be quantitatively assessed through soil quality indices (SQI) and land evaluation approaches (Rachman, 2020). Within this framework, soil quality reflects the capacity of soil to perform key functions under specific land-use systems and environmental conditions (Qihong, et al., 2025), including sustaining biological productivity, regulating water and air quality, and supporting ecosystem and human health. From an applied perspective, high-quality soils are characterized by their ability to maintain favorable physical conditions and functional stability, even under limiting or harsh climatic environments (Bünemann, et al., 2018). In this context, land suitability assessment provides a complementary decision-support tool by linking measured soil quality indicators with land-use requirements (Doran & Zeiss, 2000; Yahqub, et al., 2024), thereby enabling the identification of optimal management strategies and enhancing the resilience of food production systems (Lehmann & Bossio, 2022).

Soil quality assessment can serve as an indicator for evaluating soil management and land sustainability (AlShoumik, et al., 2024; Destika, et al., 2026) and can also identify productivity problems and inform land management and agricultural systems (Kumari, et al., 2025). For agricultural land, determining its suitability for agricultural production requires a synthesis of a range of physical and chemical factors (Maulood & Darwesh, 2020), as well as socio-economic factors, under a holistic comprehensive structure (Philippot, et al., 2023). Physical properties are determined by several parameters such as soil structure, texture, bulk density, and aggregate stability, which directly affect the hydrological functions of the soil (Pandao, et al., 2024). Chemical properties reflect the soil's ability to provide nutrients and regulate their availability, which depends on indicators such as pH, cation exchange capacity (CEC), nutrient content, and electrical conductivity (EC) (FAO & ITPS, 2020; Samaniego, et al., 2025). Soil organic carbon (SOC) stands out as one of the most important indicators, as it is a major enhancer of physical properties (such as aggregate stability and moisture retention), chemical properties (such as CEC), and biological properties (as an energy source for living organisms) (Delgado-Baquerizo, et al., 2020). Soil indicators are important tools for determining soil quality; therefore, they are selected based on their relevance to soil functions and how they affect local ecosystem services (Wang, et al., 2026). An indicator should be able to describe changes in the soil resulting from management practices (Bünemann, et al., 2018). Because land degradation occurs gradually, reflecting land management practices, if the indicator is not sensitive enough, there is a possibility that harmful changes to soil health will occur without being noticed through the study of these indicators (Paz-Ferreiro & Fu 2016; Adhikari, et al., 2025). This underscores the need for an integrated assessment of soil properties based on sensitive, impactful, and measurable indicators (Metwaly, et al., 2024).

The objective of this research isto provide an integrated vision of soil quality that contributes to enhancing conservation efforts and sustainable management of this strategic non-renewable resource.

Materials and Methods

Study Locations

This study included 40 sites from various areas of northern Nineveh Governorate within the districts of Rabia, Zummar, Sheikhan, Wana, Alqush, Faida, Bashiqa, and Telkaif (AlJawwady, 2019; AlSayegh, 2020; AlAskari, 2022; Younus, 2023; Alhamadani, 2024) (Figure 1). The longitude, latitude, and elevation coordinates (ASL) were recorded for all study sites based on the Global Positioning System (GPS) using a German-made (German eTrax 20) device (Table 1).

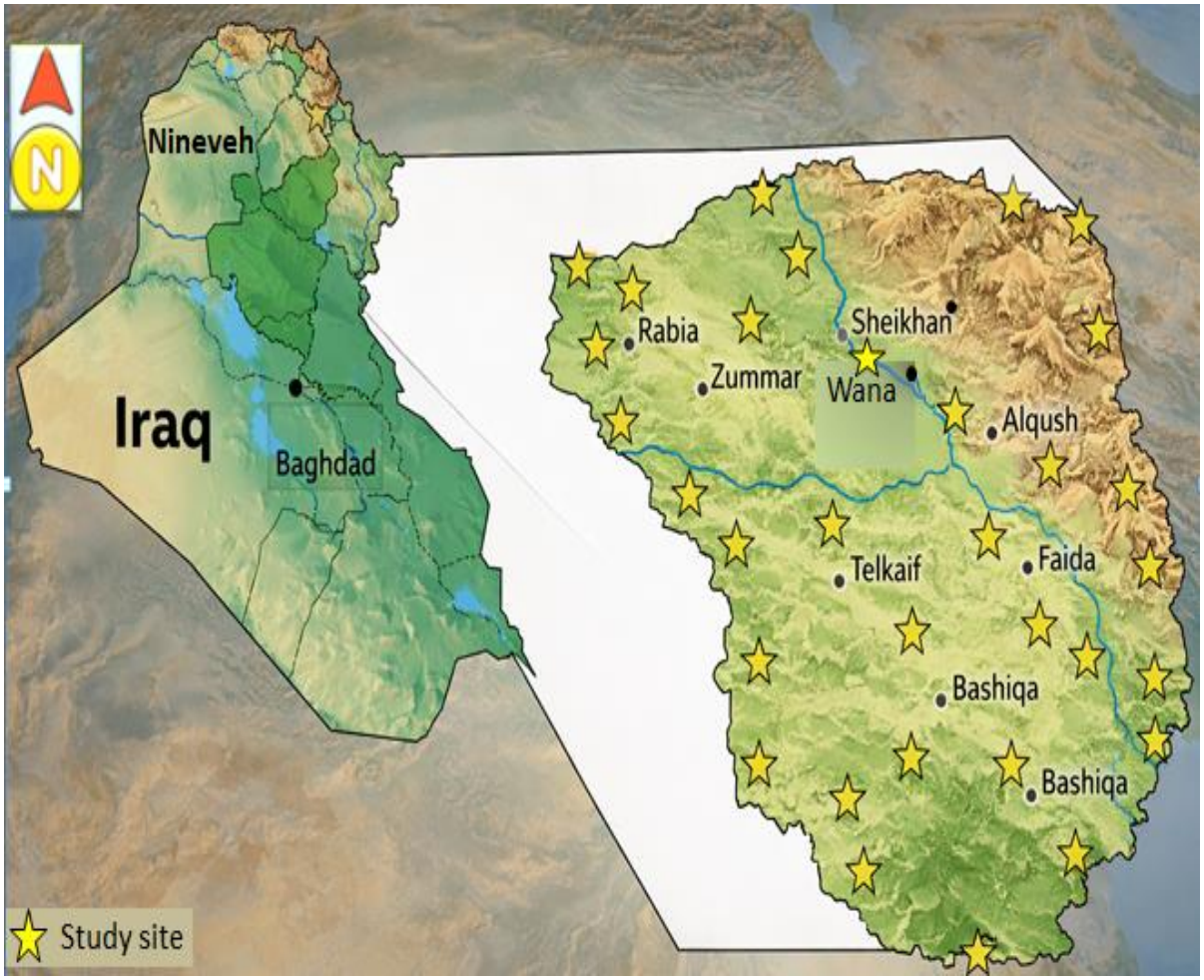


Figure 1. *Study sites in northern Nineveh Governorate within Iraq*

Table 1. *Selected sites within the study area and their GPS coordinates*

No.	Locations	E	N	ASL (m)	Land use
1	Mafri	43°33′07″	36°36′01″	330	Wheat & barely
2	Krkafr	43°31′05″	36°41′11″	345	Wheat & barely
3	Abowjna	43°38′33″	36°41′23″	387	vegetable crops
4	Gheshea	42°39′23″	36°36′58″	366	Wheat & barely
5	Shekan	42°21′38″	36°52′12″	380	Wheat & barely
6	Bardia	42°29′37″	36°47′47″	360	Wheat & barely
7	Sahela	42°20′20″	37°00′36″	453	Wheat & barely
8	Hdayma	42°29'00"	36°31'55"	320	Wheat & barely
9	Telaskf	43°08′53″	36°34′38″	354	Wheat & barely
10	Bahadra	43°14′29″	36°43′44″	545	Wheat & barely
11	Uwaynah	42°59′46″	36°26′29″	292	vegetable crops
12	Amarbet	42°56′11″	36°31′37″	296	Wheat & barely
13	Gambur	42°58′26″	36°43′23″	403	Wheat & barely
14	Shalalat	43°11′27″	36°27′18″	270	Eucalyptus
15	Fadlya	43°15′45″	36°30′20″	326	Olive
16	Mahad	43°25′14″	36°39′10″	418	Wheat & barely
17	Muskan	43°25′01″	36°36′42″	349	Peach
18	Abdlya	43°26′55″	36°27′55″	350	Wheat & barely
19	Besan	43°07′06″	36°27′58″	262	Wheat & barely
20	Batana	43°07′23″	36°33′29″	322	Wheat & barely
21	Derka	43°13′09″	36°29′16″	295	Wheat & barely
22	Barema	43°13′38″	36°32′19″	348	Wheat & barely
23	OrtKhrab	43°15′24″	36°23′57″	257	Wheat & barely
24	Drawesh	43°16′19″	36°25′53″	285	Wheat & barely
25	Basheqa	43°18′10″	36°27′31″	333	Wheat & barely
26	Dbshea	42°27'20"	36°41'10"	353	Vegetable crops
27	Msherfa	42°03'15"	36°45'31"	391	Wheat & barely
28	TelHawa	41°58'49"	36°36'26"	307	vegetable crops
29	Mome	42°02'52"	36°37'38"	405	Wheat & barely
30	Botha	42°15'50"	36°43'01"	392	vegetable crops
31	Mthaltha	42°17'53"	36°37'58"	404	Wheat & barely
32	Gelbarat	42°07'58"	36°49'42"	404	Vegetable crops
33	Mosuldum	42°52'12"	36°36'29"	392	Pastures
34	Wana	42°45'05"	36°31'20"	251	Vegetable crops
35	Telkef	43°06′34″	36°27′34″	257	Wheat & barely
36	Alqush	43°05′30″	36°42′19″	461	Wheat & barely
37	Quba	43°02′45″	36°24′07″	215	Vegetable crops
38	Manara	42°56′50″	36°35′52″	330	Wheat & barely
39	Gambor	43°01′07″	36°42′03″	388	Wheat & barely
40	Sharia	42°59′06″	36°46′28″	650	Wheat & barely

Surface soil samples were collected from a depth of 0–20 cm, air-dried, and sieved through a 2 mm sieve. Soil pH and electrical conductivity (EC) were measured in a soil:water suspension using standard electrodes. Soil organic carbon (OM) was determined by the Walkley–Black method, while calcium carbonate ($CaCO_3$) content was determined using the titration method. Soil texture was determined using the hydrometer method. Bulk density (BD) was measured using the core method, and cation exchange capacity (CEC) was determined using the ammonium acetate method at pH 7. All analyses were conducted

according to standard procedures as described in Page et al., (1982) methods of soil analysis. The results of these analyses are presented in Table 2.

Table 2. *Physical, chemical and morphological properties used in the study*

No.	pH	EC (dS m^{-})	OM	$CaCO_3$	Texture	BD (Mg m^{-3})	CEC ($cmol_c$ kg^{-1})	Slope (%)	Drainage	ED (cm)	VC (%)
			(g kg^{-1})								
1	7.2	1.81	16.6	110.0	ClL	1.40	39.45	3–4	W	100	20-25
2	7.2	0.70	13.8	345.0	Cl	1.32	16.50	2–3	W	100	20-25
3	7.3	0.36	19.0	265.0	LCl	1.26	21.36	1–2	W	100	>75
4	7.5	0.27	15.0	425.0	Cl	1,33	15.00	3-4	W	85	20-25
5	7.5	0.20	17.5	335.0	ClL	1.33	16.40	2–3	W	100	20-25
6	8.1	0.18	17.2	350.0	Cl	1.29	17.00	2–3	W	100	20-25
7	7.5	0.18	21.0	310.0	Cl	1.33	15.00	2–3	W	100	20-25
8	8.0	0.70	10.0	300.0	Cl	1.39	22.76	2–3	W	100	20-25
9	7.8	0.60	17.0	225.0	Cl	1.38	15.90	3-5	W	100	20-25
10	7.9	0.55	18.4	240.0	ClL	1.25	14.00	5-6	W	100	20-25
11	7.7	1.34	16.0	340.0	SClL	1.21	21.70	1-2	W	100	20-25
12	7.0	0.23	10.3	230.0	Cl	1.28	17.00	3-4	W	100	20-25
13	8.0	0.53	15.2	351.0	Cl	1.31	11.00	4-5	W	100	20-25
14	7.8	0.49	18.9	301.0	SiClL	1.31	23.91	2-3	W	100	>75
15	7.8	0.28	15.1	256.0	Cl	1.36	29.89	2-3	W	100	>75
16	7.2	0.26	18.9	104.0	Cl	1.29	35.29	6-7	W	90	20-25
17	7.9	0.33	19.0	292.0	Cl	1.29	32.60	6-7	M	85	>75
18	7.3	0.30	23.4	134.5	Cl	1.27	24.45	8-9	M	75	50-75
19	8.3	0.68	10.5	268.4	ClL	1.21	26.09	2-3	W	100	20-25
20	8.0	0.85	9.3	311.6	SiL	1.31	31.52	5-6	W	90	20-25
21	8.3	0.40	13. 5	302.0	SiL	1.40	22.83	5-6	M	90	20-25
22	8.2	0.52	15.2	340.0	SiL	1.3	26.09	5-6	W	90	20-25
23	8.2	0.43	11.2	236.6	SiL	1.24	21.74	5-6	W	90	20-25
24	8.3	0.43	6.6	273.2	L	1.36	19.57	5-6	W	90	20-25
25	8.3	0.37	7.3	268.4	SiL	1.24	25.00	5-6	W	90	20-25
26	7.8	0.71	19.5	200. 0	L	1.47	25.25	0-1	W	100	>75
27	7.4	2.30	10.3	325.9	SiL	1.32	16.50	0-1	W	100	50-75
28	7.5	1.50	23.1	215.0	SiL	1.33	20.30	0-1	W	100	>75
29	7.5	1.52	23.1	305.0	L	1.70	14.50	0-1	W	100	50-75
30	7.4	2.96	15.2	296.7	L	1.25	16.35	0-1	W	100	>75
31	7.4	0.79	19. 5	175.0	LCl	1.33	10.35	0-1	W	100	50-75
32	7.4	0.71	16.1	297.2	SiClL	1.53	22.50	0-1	W	100	>75
33	7.9	0.50	9.3	310.0	LS	1.32	21.25	7-8	M	75	< 25
34	7.8	1.30	18.6	225.0	L	1.26	24.50	0-1	W	100	>75
35	7.3	0.50	17.0	239.0	Cl	1.35	23.55	2-3	W	100	25-75
36	8.1	0.52	17.6	252.0	LCl	1.21	23.60	6-7	W	100	20-25
37	7.3	3.49	18.0	300.0	Cl	1.28	26.40	0-2	W	100	>75
38	7.0	0.34	13.1	210.0	Cl	1.21	20.55	3-4	W	100	25-75
39	8.0	0.53	15.2	351.0	Cl	1.31	21.30	7-8	W	100	20-25
40	7.9	0.40	18.4	181.4	ClL	1.38	22.30	2-3	W	100	20-25

* ClL: clay loam, Cl: clay, L: loam, LS: loamy sand, SiClL: silty clay loam, LCl: loamy clay, SiL: silty loam, SClL: sandy clay loam, W: well drained, M: medium drained

Soil quality assessment according to SQI and SQI-plus

The SQI-plus classification scheme (0–5 scale) was established by integrating the FAO land evaluation concepts with subsequently developed modifications of soil quality index methodologies, according to the Rachman (2019) methodology, which is based on the Weighted Additive Index method. The calculation process included two main steps:

1- **Selection of indicators:** Eleven attributes were selected to represent the physical, chemical, and morphological functions of the soil: organic matter (OM), pH, cation exchange capacity (CEC), calcium carbonate ($CaCO_3$), electrical conductivity (EC), texture, bulk density (BD), effective depth (ED), drainage, slope, and vegetation cover (VC).

2- Weight allocation and calculation: Based on the Rachman (2019) and Gutierrez)2024 (methodology and relying on the Weighted Additive Index (WAI), relative weights (Wi) were determined for each attribute that reflect its importance in sustainable productivity, with the greatest weight given to OM and ED (Table 3). The data were converted to standard values ranging from 0.1 to 1.0 in the SQI model (Table 4) and from 0 to 5 in the SQI-Plus model (Table 5), using scoring functions based on the principle of "more is better", "less is better", or "optimal", taking into account the calcareous and climatic characteristics of the soils of northern Iraq. The SQI-Plus model is not limited to numbers; it also includes symbols that indicate limiting factors. Letters are added to any criterion scoring 2.00 or lower, classifying these criteria as low and thus considered limiting factors.

Table 3. *Key parameters (Wi) for assessment of Soil Quality Index (SQI)*

Indicator	Wi	Scientific and economic justification
OM	0.15	Driver of fertility and vitality
pH	0.08	Affects the availability of elements
CEC	0.09	Expresses the soil's ability to retain nutrients
EC	0.09	Salinity is an indicator crop selection
$CaCO_3$	0.07	High concentrations affect the physical properties
Texture	0.10	Affects water permeability and nutrient retention
BD	0.07	Indicator of soil compaction and porosity
Depth	0.12	Water and root growth are crucial in agriculture
Drainage	0.05	Essential for root aeration
Slope	0.10	Major factor in soil erosion
VC	0.08	Basic in soil fertility and improved soil structure.
Total	1.00	Sum of the weights must equal one

The value of each attribute (after scored and weighted to a standard value from 0 to 1) is multiplied by its additive method, according to the Standard Weighted Sum Equation (Andrews, et al., 2004):

$SQI = \sum_{i=1}^{n}(Wi \times Si)$

Where: SQI= Final value of the SQI index, Wi= weighting coefficient for each criterion, representing the criterion's significance and impact, Si= score assigned to the criterion based on laboratory or field analysis results, n= number of criteria used.

Table 4. *Criteria used to score each parameter according Andrews et al. (2002)*

Characteristic	Range 1	Score	Range 2	Score	Range 3	Score	Range 4	Score
OM (%)	> 3.0	1.0	2.0– 3.0	0.7	1.0– 2.0	0.4	< 1.0	0.1
Depth (cm)	> 100	1.0	50– 100	0.7	25– 50	0.4	< 25	0.1
EC (dS m^{-1})	< 2.0	1.0	2 – 4	0.8	4 – 8	0.5	8 – 16	0.2
pH	6.5–7.8	1.0	7.8– 8.4	0.7	> 8.4	0.3	—	—
CEC (cmolc kg^{-1})	> 25	1.0	15– 25	0.7	5– 15	0.4	< 5	0.1
Texture	L, SiL	1.0	C, SiC	0.7	S	0.3	—	—
Slope (%)	0 – 2	1.0	2– 8	0.7	8– 15	0.4	> 15	0.1
$CaCO_3$ (%)	< 10	1.0	10– 20	0.7	20– 30	0.4	> 30	0.1
BD (g cm^{-3})	< 1.3	1.0	1.3– 1.5	0.7	1.5– 1.7	0.3	> 1.7	0.1
Drainage	VG	1.0	G	0.8	M	0.5	B	0.1
VC (%)	> 75	1.0	50– 75	0.7	25– 50	0.4	< 25	0.1

Remarks: C= clay; SiL= silty loam; L= loam; SiC= silty clay; S= sand; VG= very good; G= good; M= moderate; B= bad

Table 5. *Criteria used to score each parameter according to Rachman (2019b)*

Parameters	0	1	2	3	4	5
OM %	<0.3	0.3-0.6	0.6-1.0	1.0-1.8	1.8-3.0	> 3.0
depth cm	<10	10-20	20-40	40-60	60-80	> 80
EC (dS m^{-1})	> 8.0	4-8	2-4	1-2	0.5-1	< 0.5
pH	<4.5 or >9.0	4.5-5.5	5.5 -6.5	8.0-8.5	6.5-7.5	7.5-8.0
CEC cmolc kg^{-1}	<5	5-10	10-15	15-25	25-40	> 40
Texture	S	LS	SL	SC, SiC	C, Si	L, SiL, SCL, SiCL, CL
Slope %	>30	20–30	15–20	8–15	3–8	<3
$CaCO_3$ (%)	> 30	30-20	20-15	15-10	10-5	< 1
BD g cm^{-3}	>1.7	1.7-1.5	1.5-1.3	1.3-1.1	1.1-0.9	< 0.9
Drainage	VP	P	SP	M	G	VG
VC (%)	< 10	10–25	25-40	40-60	60-80	> 80

Remarks: C= clay; SiL= silty loam; L= loam; SiC= silty clay; S= sand; Si= silt; SC= sandy, clay; CL= clay loam; SiL= silty loam; SL= sandy loam; SiCL= silty clay loam; SCL= sandy clay loam; LS= loamy sand, VP= very poor, P= poor, SP= slightly poor, M= moderate, G= good, VG= very good

Table 6. *SQI Classification according to Andrews et al, (2002) and Rachman (2019b)*

SQI-plus Score	Classification	SQI Score	Classification
> 0.8	Very High Quality	$x \leq 2.0$	Very bad
0.6-0.8	High Quality	$2.0< x \leq 2.5$	Slightly Bad
0.4-0.6	Moderate	$2.5< x \leq 3.0$	Bad
< 0.4	Low Quality	$3.0< x \leq 3.5$	Medium
		$3.5< x \leq 4.0$	Slightly good
		$4.0< x \leq 4.5$	Good
		$x > 4.5$	Very good

Remarks: x = SQI score

Statistical analyses

All statistical analyses were performed using IBM SPSS Statistics version 16.0 software (SPSS, Inc., Chicago, IL, USA). Descriptive statistics were calculated, and data were screened for outliers and normality prior to further analysis. Soil properties were transformed into standardized scores using predefined scoring functions, and Soil Quality Index (SQI) and SQI-plus values were computed using the WAI approach. Principal Component Analysis (PCA) was applied to identify the most influential indicators and to determine the most suitable model structure. Sensitivity analysis and comparative evaluation between SQI and SQI-plus were conducted, and differences among groups were tested using ANOVA at a significance level of $p \leq 0.05$.

Results and Discussion

1. Methodological comparison: SQI vs. SQI-plus

The assessment of soil quality used in the study reveals a distinct divergence between the traditional SQI and the modified SQI-Plus model in Table 7. Based on the classification criteria in Table 6, most sites were categorized as "High Quality" under the SQI model, with scores ranging from 0.574 to 0.781. When compared SQI-plus with the conventional SQI approach, the application of the SQI-plus methodology-integrating FAO land evaluation principles with a weighted additive index-resulted in a redistribution of sites toward the Medium, Slightly good, and Bad classes. Specifically, SQI-plus classified 13 sites as Slightly good, 15 as Medium, and only two as Bad, indicating a more differentiated assessment of soil quality. This shift highlights the superior sensitivity of SQI-plus in capturing the influence of key soil attributes and demonstrates its enhanced capability to reflect actual soil quality conditions compared with traditional linear SQI models.

2. Analysis of indicator weighting and sensitivity

The research utilized eleven physical, chemical, and morphological indicators, each assigned a weighting coefficient (Wi) based on its scientific and economic justification as shown in Table 3. OM and ED were assigned the highest weights (0.15 and 0.12, respectively), identifying them as the primary drivers of soil fertility and root development in the region. The use of these weights in the equation

SQI = $\sum_{i=1}^{n}(Wi \times Si)$ ensures that the final index value reflects the relative importance of each property in sustaining productivity. The lower weights assigned to factors like drainage (0.05) suggest that while essential for aeration, they were secondary to the foundational roles of fertility and soil volume in this specific environmental context.

3. Impact of physiochemical and morphological properties on quality scores

Table 7 shows that OM and $CaCO_3$ are the most common and influential factors in the entire study area, accounting for 87.5%, followed by VC at 60% and BD at 18%. The least common determinants are salinity (EC) at 7.5% and CEC at 5%. The results also showed that site number 13 was the most affected, exhibiting five determinants (OM, $CaCO_3$, BD, VC, and CEC), leading to its classification as a "bad" soil. Sites (2, 4, 5, 7, 8, 9, 21, 35, and 40) were each affected by four determinants, most commonly OM, $CaCO_3$, BD, and VC. Site number 18 was the least affected, with only one determinant, OM, being identified.

Table 7. *Results of soil quality assessment using SQI and SQI-plus*

No.	SQ1 Score	Classification	SQ1-plus Score	Classification
1	0.694	High Quality	3.47OM, BD, VC	Medium
2	0.625	High Quality	3.13OM, $CaCO_3$, BD, VC	Medium
3	0.745	High Quality	3.73 OM, $CaCO_3$	Slightly good
4	0.598	Moderate	2.99 OM, $CaCO_3$, BD, VC	Bad
5	0.625	High Quality	3.13 OM, $CaCO_3$, BD, VC	Medium
6	0.622	High Quality	3.11 OM,$CaCO_3$, VC	Medium
7	0.643	High Quality	3.22 OM, $CaCO_3$, BD, VC	Medium
8	0.622	High Quality	3.11 OM, $CaCO_3$, BD, VC	Medium
9	0.622	High Quality	3.11 OM, $CaCO_3$, BD, VC	Medium
10	0.616	High Quality	3.08 OM, $CaCO_3$, CEC, VC	Medium
11	0.646	High Quality	3.23 OM, $CaCO_3$, VC	Medium
12	0.667	High Quality	3.34 OM, $CaCO_3$, VC	Medium
13	0.574	Moderate	2.87 OM, $CaCO_3$, BD, VC,CEC	Bad
14	0.703	High Quality	3.52 OM, $CaCO_3$, BD	Slightly good
15	0.721	High Quality	3.61 OM, $CaCO_3$, BD	Slightly good
16	0.715	High Quality	3.58 OM, VC	Slightly good
17	0.693	High Quality	3.47 $CaCO_3$	Medium
18	0.702	High Quality	3.51OM	Slightly good
19	0.670	High Quality	3.35 OM, $CaCO_3$, VC	Medium
20	0.658	High Quality	3.29 OM, $CaCO_3$, BD, VC	Medium
21	0.606	High Quality	3.03 OM, $CaCO_3$, BD, VC	Medium
22	0.673	High Quality	3.37 OM, $CaCO_3$, VC	Medium
23	0.652	High Quality	3.26 OM, $CaCO_3$, VC	Medium
24	0.673	High Quality	3.37 OM, $CaCO_3$, BD, VC	Medium
25	0.778	High Quality	3.89 OM, $CaCO_3$, BD, VC	Slightly good
26	0.697	High Quality	3.49 OM, $CaCO_3$, BD	Medium
27	0.778	High Quality	3.89 EC, $CaCO_3$	Slightly good
28	0.699	High Quality	3.50 $CaCO_3$	Medium
29	0.763	High Quality	3.82 OM, $CaCO_3$, BD	Slightly good
30	0.724	High Quality	3.62 OM, EC, $CaCO_3$	Slightly good
31	0.747	High Quality	3.74 OM, $CaCO_3$, BD	Slightly good
32	0.606	High Quality	3.03 OM,$CaCO_3$, BD	Medium
33	0.772	High Quality	3.86 OM, $CaCO_3$, BD, VC	Slightly good
34	0.691	High Quality	3.46 OM, $CaCO_3$	Medium
35	0.694	High Quality	3.47 OM,$CaCO_3$, BD, VC	Medium
36	0.781	High Quality	3.91 OM, $CaCO_3$, VC	Slightly good
37	0.712	High Quality	3.56 OM, EC, $CaCO_3$	Slightly good
38	0.643	High Quality	3.22 OM, $CaCO_3$, VC	Medium
39	0.643	High Quality	3.22 OM, $CaCO_3$, VC	Medium
40	0.694	High Quality	3.47 OM, $CaCO_3$, BD, VC	Medium

Soil quality assessment based on SQI-plus evaluation

The results shown in Table 7, along with the radar-based frequency analysis (Figure 2), reveal a consistent pattern explaining the spatial decline in Soil Quality Index-plus (SQI-plus) values across the study sites. The decline in SQI-plus was primarily associated with the

prevalence of reduced OM, recorded in 37 sites (92.5%), and increased $CaCO_3$ content, observed in 34 sites (85%). The widespread prevalence of these two factors, affecting more than 85% of the studied sites, indicates that OM depletion and carbonate accumulation are the main drivers of soil quality degradation in the region. Reduced VC and increased bulk density (BD) showed moderate frequencies, affecting 62.5% and 60% of the sites, respectively, suggesting they are less specific in exacerbating soil function degradation than OM and $CaCO_3$. In contrast, EC and CEC were determined at less than 10% of sites, explaining their minimal contribution to Soil Quality Index-plus (SQI-plus) values across sites. This distribution pattern, taken together, suggests that the low SQI-plus values primarily reflect the deterioration of soil chemical and biological properties, particularly under arid and semi-arid environmental conditions. These findings are consistent with the conclusions of Kiani et al. (2017).

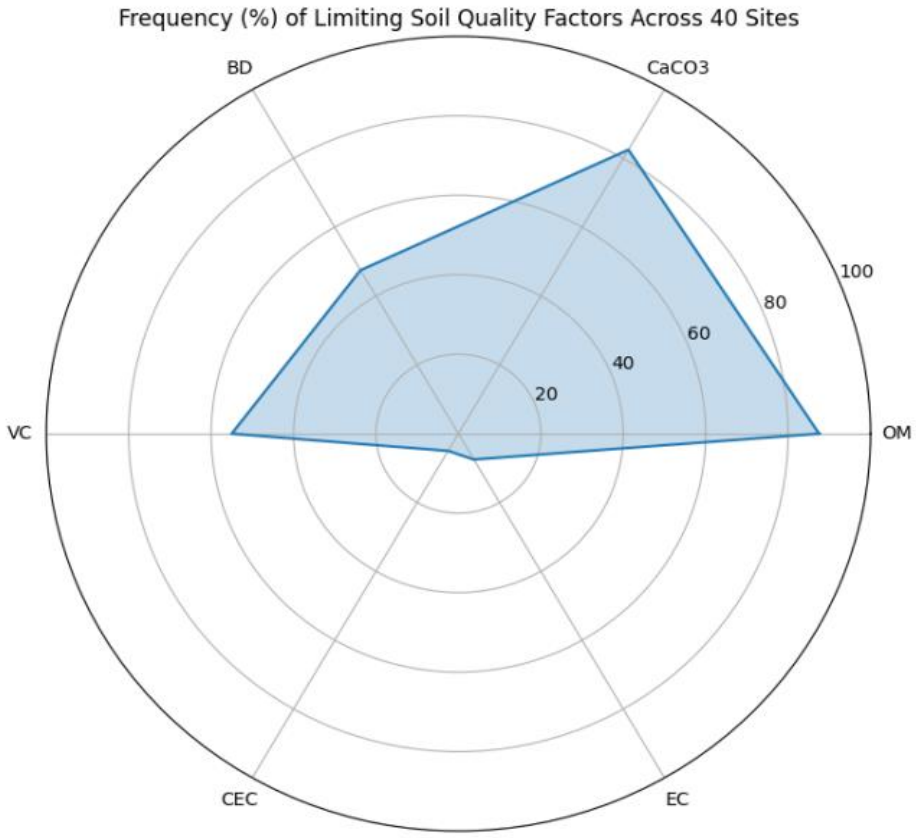


Figure 2. *Radar chart showing the percentage frequency of limiting soil quality indicators across the forty sampling sites based on SQI-Plus analysis*

To further define the balance between soil indicators, the radar polygon area (RPA) for each site was calculated and statistically correlated with the Soil Quality Index (SQI-Plus) results (Figure 3). The analysis showed a strong positive correlation ($r = 0.92$, $p < 0.0001$), confirming that increasing polygon area is directly proportional to improved soil quality. Sites classified as "fairly good" exhibited larger and more balanced radar polygons, while sites classified as "average" and "poor" showed shrunken and irregular polygons, reflecting selective constraints on the indicators.

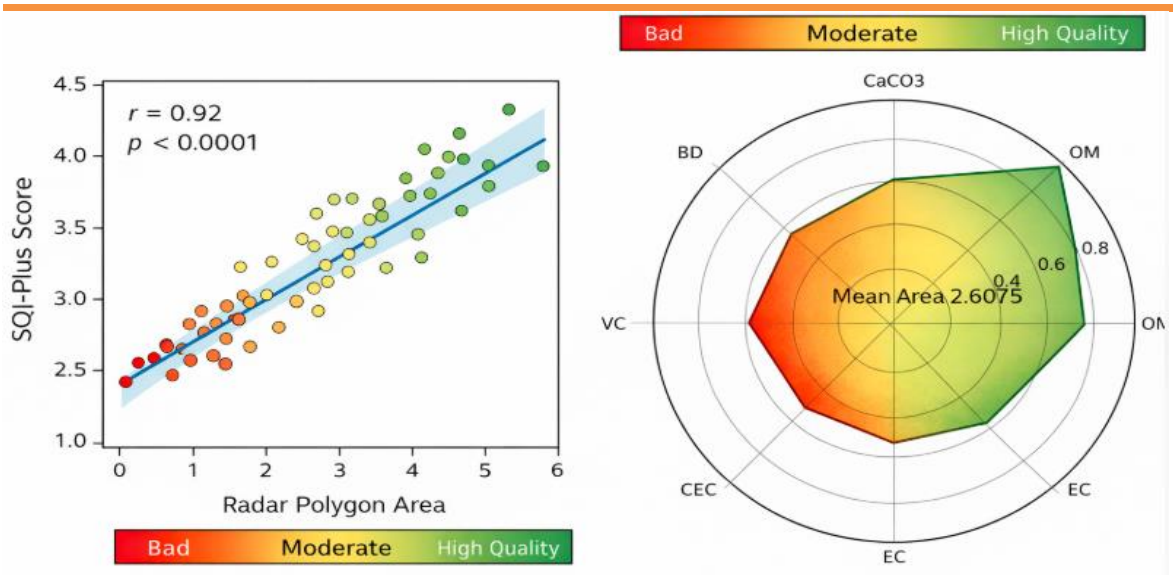


Figure 3. *Positive correlation between radar polygon area and Soil Quality Index (SQI-Plus) scores across the 40 sampling sites. Pearson's correlation coefficient (r = 0.92, p < 0.0001) indicating positive relationship between radar polygon area and SQI-Plus scores*

The predominance of OM and $CaCO_3$ as limiting factors indicates the need to prioritize OM enhancement and carbonate-related soil structure improvement in soil rehabilitation strategies. The limited effect of electrical conductivity also suggests that salinity is not a limiting factor for soil degradation in the studied area.

The linear relationship between RPA and Soil Quality Index (SQI-Plus) was assessed using Pearson's correlation coefficient. The analysis showed an r = 0.92 and a p < 0.0001, indicating a very strong positive linear relationship between the radar-derived geometric equilibrium and the composite soil quality.

Table 8. *ANOVA Table*

Source	df	SS	MS	F	p-value
Regression	1	6.82	6.82	219.4	<0.0001
Residual	38	1.18	0.031	—	—
Total	39	8.00	—	—	—

Statistical Interpretation

The results of the analysis of variance (ANOVA) confirmed that the linear regression model was statistically significant [F(1,38) = 219.4, p < 0.0001], explaining 85% of the variance in the Soil Quality Index (SQI-Plus) scores (R^2 = 0.85). The high F-value and very low mean squared residuals indicate that the radar polygon area is a highly reliable indicator of integrated soil quality performance at the 40 sampling sites.

Conclusion

The results demonstrated that the SQI-Plus model exhibits greater sensitivity than the conventional SQI model in assessing soil quality, as it reclassified sites previously categorized as "High Quality" into more realistic classes such as "Medium" and "Bad," with strong statistical reliability (R^2= 0.92). Soil quality in northern Iraq was found to be primarily constrained by biological and chemical factors rather than physical ones, particularly low organic matter (92.5%) and high calcium carbonate (85%), while poor vegetation cover and high bulk density contributed to degradation in over 60% of sites, highlighting the vulnerability of soil structure and fertility under arid and semi-arid conditions. Organic matter

(0.15) and effective depth (0.12) emerged as the most influential weighted indicators for sustaining productivity, while Site 13 was identified as the most degraded due to multiple limiting factors, resulting in its classification as "Bad."

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