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Assessment and Mapping of Soil Quality Degradation Indicators for Some Desert Lands Using Geospatial Techniques

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ABSTRACT

The aim of this study was to assess soil quality degradation in selected desert lands and to produce their geospatial maps using Geographic Information Systems (GIS). The study was conducted in Thi-Qar Governorate in southern Iraq, covering an area of 99.12 km². A total of 33 surface soil samples (0–30 cm) were collected, in addition to describing five soil pedons distributed across the study area following the guidelines of the Soil Survey Staff (2022). Physical indicators (texture, bulk density, porosity, and electrical conductivity), chemical indicators (gypsum, calcium carbonate, electrical conductivity, soil reaction, sodium adsorption ratio, and exchangeable sodium percentage), and fertility indicators (organic matter, available nitrogen, available phosphorus, and available potassium) were measured. Spatial distribution maps of soil quality indicators were generated using the Inverse Distance Weighting (IDW) spatial interpolation technique in ArcGIS. The results showed that the Soil Physical Index fell within the low class, representing 98.04 km² (98.91%). The Soil Chemical Index was distributed between the medium class with an area of 36.83 km² (37.16%) and the high class covering 62.29 km² (62.84%). The Soil Fertility Index was classified into three classes, with the medium class forming the largest area (91.27 km²). The Soil Quality Index (SQI) itself was distributed between two classes: the moderate class, which comprised 67.36 km² (67.96%), and the low class, which covered 31.76 km² (32.04%). This indicates that most of the soils fall within the moderate-to-poor quality categories that are amenable to improvement through sustainable management. The study concludes that integrating field and laboratory analyses with digital geospatial processing constitutes an effective tool for monitoring environmental changes and degradation in the soils of Thi-Qar.

Keywords: Soil management, desert land degradation, soil quality indicators, physical soil indicators, chemical soil indicators, soil fertility indicators.

INTRODUCTION

Assessing soil quality and monitoring land degradation in arid and semi-arid environments are among the most critical environmental and agricultural issues due to their direct impact on the sustainability of natural resources, agricultural productivity, and food security (FAO, 2022). Thi-Qar Governorate in southern Iraq represents a distinct environmental setting due to its geomorphological diversity and alluvial soils; however, it is simultaneously subjected to various forms of desertification and degradation driven by harsh climatic conditions characterized by high temperatures, low and irregular rainfall, weak vegetation cover, and recurring dust storms. These factors collectively contribute to reduced fertility, increased salinity, surface crusting, and higher susceptibility to wind and water erosion, making soil quality assessment essential for understanding degradation dynamics and developing appropriate management strategies (Lal, 2020; Borrelli et al., 2020).

Soil is an integrated ecological system influenced by the interaction of the five soil-forming factors: parent material, climate, topography, organisms, and time (FAO, 2022). Any disruption in this balance leads to changes in the physical, chemical, and pedological properties of soil, which manifest as land degradation phenomena such as salinization, surface crust formation, organic matter depletion, and structural deterioration. Water and wind erosion are among the most significant processes responsible for the removal of the nutrient-rich topsoil layer, leaving behind a coarse, nutrient-poor surface known in geomorphological literature as *desert pavement* or *rocky diamicton* (Brady & Weil, 2019; Lal, 2020).

These environmental phenomena have led to the emergence of two interrelated concepts: *land degradation* and *desertification*. The former refers to the decline in productivity across all climatic regions, whereas the latter is specific to arid, semi-arid, and dry sub-humid areas (UNCCD, 2023). Desertification is one of the most pressing environmental challenges in Iraq, resulting in the loss of agricultural soil fertility and reduced productivity due to both natural and anthropogenic drivers, including climate change, poor water resource management, weak vegetation cover, and land misuse (UNEP, 2022; Qadir et al., 2024).

Within this context, the MEDALUS model (Mediterranean Desertification and Land Use) has emerged as a comprehensive scientific framework for assessing environmental sensitivity to desertification and land degradation. It relies on a set of quantitative indicators that include soil quality, climate, vegetation cover, and land management (Kosmas et al., 2014; Salvati & Bajocco, 2011). The model has proven effective in identifying environmentally fragile areas and has been adapted to suit the dry conditions of West Asia, including the Iraqi environment (Borrelli et al., 2020; Yousif et al., 2025).

The Soil Quality Index (SQI) is one of the core components of the MEDALUS model. It is a composite indicator reflecting the integrated interaction of soil physical, chemical, and fertility properties, providing a quantitative measure of soil capacity to support plant growth and sustain biological activity (Karlen et al., 2021; Lal, 2023). The calculation of SQI depends on key attributes such as texture, bulk density, porosity, organic matter, salinity, soil pH, calcium carbonate content, and cation exchange capacity, which serve as precise indicators of soil condition and environmental functionality (FAO, 2022; Mbarki et al., 2023).

This study aims to evaluate and map the physical, chemical, and fertility degradation indicators of soil quality and to derive the Soil Quality Index (SQI) for selected desert lands in Thi-Qar Governorate. The goal is to determine their sensitivity to degradation and desertification and to provide a spatial and scientific knowledge base that supports sustainable land resource management and improves land-use efficiency in Iraq's arid environments.

MATERIALS AND METHODS

Study Area

The study was conducted in Thi-Qar Governorate in southern Iraq, encompassing an area of 99.13 km² (equivalent to 9,913 hectares). The area lies between longitudes 45°34'00"–45°50'30" E and latitudes 31°47'30"–31°53'30" N (Figure 2). Sampling locations were determined using topographic maps, land-use maps, and recent satellite imagery, in addition to consulting farmers and local experts to verify field suitability. Coordinates of all locations were accurately recorded using a Garmin GPSMAP 64sx device with ±3 m accuracy, to allow precise linkage with laboratory analyses and satellite-derived data (Figure 1).

The study area lies within desert lands characterized by arid and semi-arid climatic conditions, where annual rainfall ranges between 27 and 245 mm, with an average of 118.53 mm (33-year mean). Minimum temperatures reach 22.7°C, maximum temperatures 29.3°C, and the overall mean temperature is 26°C, peaking during July and August at approximately 40.5°C, and exceeding this value in some years (Figure 2). The topography varies from flat to gently undulating, with slopes not exceeding 7% and elevations ranging from 6 to 23 meters based on the

Digital Elevation Model (DEM). The soils are predominantly coarse-textured and experience sand movement. Some areas have been treated chemically with petroleum derivatives, while others suffer from salinization.

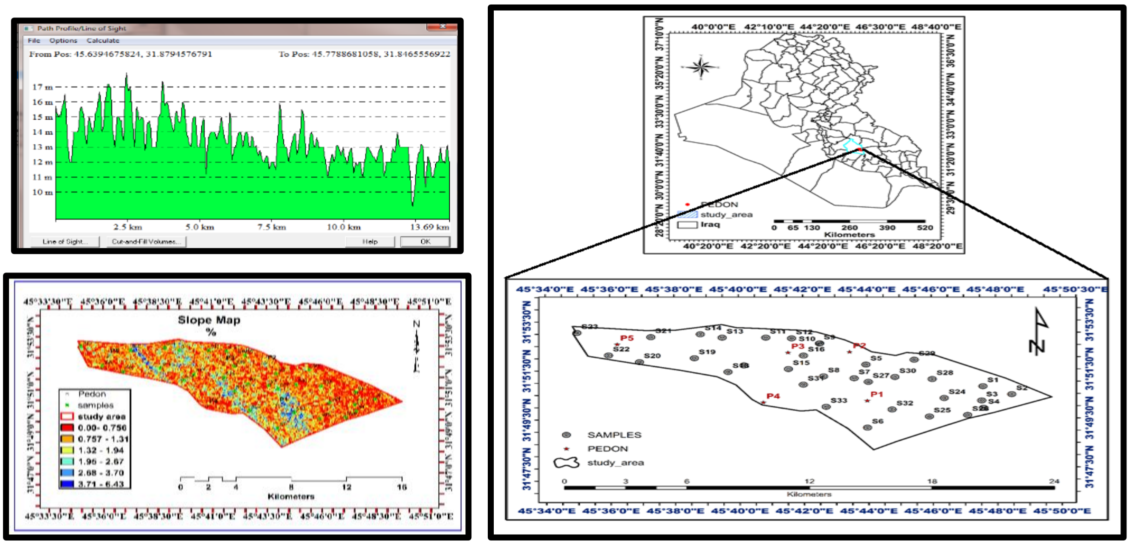
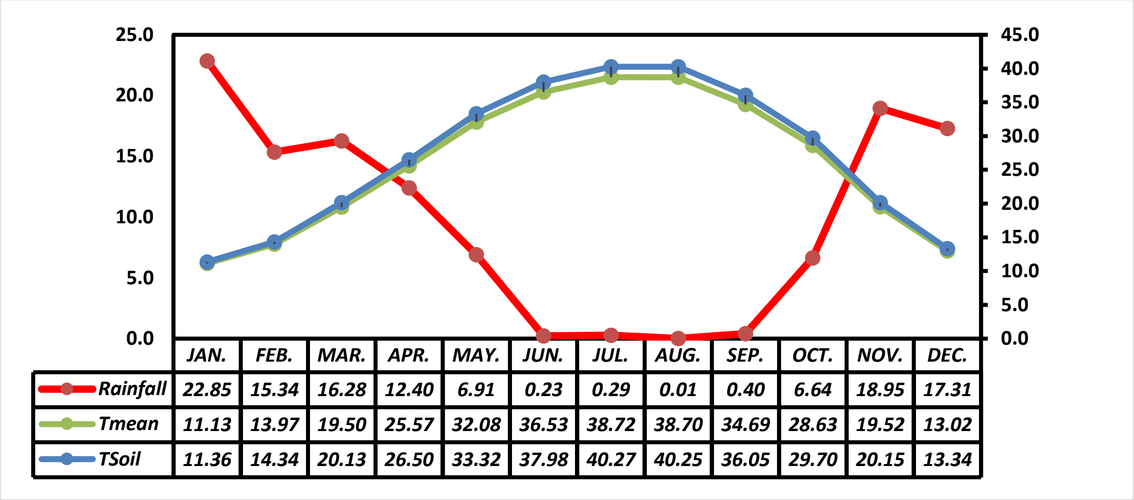


Figure (1) Maps of soil sample distribution in the study area and the slope ratio.



	JAN.	FEB.	MAR.	APR.	MAY.	JUN.	JUL.	AUG.	SEP.	OCT.	NOV.	DEC.
Rainfall	22.85	15.34	16.28	12.40	6.91	0.23	0.29	0.01	0.40	6.64	18.95	17.31
Tmean	11.13	13.97	19.50	25.57	32.08	36.53	38.72	38.70	34.69	28.63	19.52	13.02
TSoil	11.36	14.34	20.13	26.50	33.32	37.98	40.27	40.25	36.05	29.70	20.15	13.34

Figure (2): Some climatic data for the study site for the period 1992-2024https://power.larc.nasa.gov/data-access-viewer/

Morphological Description and Sample Collection:

Five soil pedons were selected across the study area based on the variability in soil characteristics, existing environmental problems, and degradation processes affecting the region. The pedons were morphologically described following the guidelines of the U.S. Soil Survey Staff (2022). Soil samples were then collected from each horizon to observe vertical variations within the soil profile. In addition, 33 surface soil samples (0–30 cm) were collected for laboratory analysis.

Laboratory Work and Procedures:

Soil texture fractions were determined using the method of Gee and Bauder (1986), and bulk density was measured using the core method as described by Black (1965). Total porosity was subsequently calculated from the mathematical relationship between bulk and particle density. Soil hydraulic conductivity was estimated using the predictive equation of Petryk et al. (2023), supported by recent studies linking soil structure, porosity, and hydraulic properties (Basile et al., 2022; Mandal et al., 2023). The physical erodibility index (EIROM) was calculated using Bouyoucos' equation (1962), which relates textural properties to aggregate stability and erosion hazard.

For the chemical analysis, electrical conductivity (EC) and soil reaction (pH) were measured in a 1:1 soil–water extract as described by Page et al. (1982). Gypsum content was determined using the acetone precipitation method according to Richards (1954). Calcium carbonate content ($CaCO_3$) was estimated following the procedure of Ryan et al. (1996). Organic matter was determined according to Tandon (1998). Soluble ions in both soil and irrigation water were analyzed following Richards (1954). The soluble cations and anions (Na^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}, HCO_3^-) were determined using standard protocols (FAO, 2022), and their values were used to compute the

Sodium Adsorption Ratio (SAR) and Exchangeable Sodium Percentage (ESP) following Richards (1954), supported by recent literature linking salinity–sodicity interactions to soil structural degradation in arid environments (Wang et al., 2021; Qadir et al., 2021).

Fertility indicators included total nitrogen determined by the Semi-Micro Kjeldahl method (Bremner in Page et al., 1982), available nitrogen using the Micro Kjeldahl method (Bremner, 1965), available phosphorus extracted using the Olsen et al. (1954) method, and available potassium extracted with calcium chloride ($CaCl_2$) and measured using a flame photometer (Ryan et al., 2019) (Table 1).

Calculation of Soil Quality Index (SQI)

The Soil Quality Index and its sensitivity to desertification were estimated based on the quantitative analysis of several soil parameters measured across the study sites (Table …). The evaluation included a description, criterion, and assigned weight for each parameter incorporated into the assessment equations. These parameters were classified into physical, chemical, and fertility indicators.

Following an extensive literature review, eight key soil properties were selected to represent the sensitivity of soils to degradation and desertification with high accuracy and reliability. This selection was based on evidence showing that using a limited number of properties may lead to inconsistent evaluation outcomes, shifting between low, moderate, and good classes, ultimately affecting assessment precision. The selected attributes were adopted based on FAO (2006), Yousif et al. (2025), Khalaf and Hussien (2021), Ashraf (2020), Kosmas (1999, 2014), and Hassan (2024) (Table 2).

The indices were computed using the following equations:

(1) Soil Physical Index:

Soil physical index=(Texture×BD×Hydraulic conductivity×Porosity×EIROM×Gravel %×Slope)1/7\text{Soil physical index}=(\text{Texture}\times\text{BD}\times\text{Hydraulic conductivity}\times \text{Porosity}\times\text{EIROM}\times\text{Gravel\%}\times\text{Slope})^{1/7}Soil physical index=(Texture×BD×Hydraulic conductivity×Porosity×EIROM×Gravel %×Slope)1/7
(Hazelton et al., 2016)

(2) Soil Chemical Index:

Soil chemical index=(pH×EC×CaCO3×CaSO4·2H2O×CEC×ESP×SAR)1/7\text{Soil chemical index} = (\text{pH}\times\text{EC} \times \text{CaCO}_{3} \times \text{CaSO}_{4}\cdot 2\text{H}_{2}\text{O} \times \text{CEC} \times \text{ESP}\times\text{SAR})^{1/7}Soil chemical index=(pH×EC×CaCO3×CaSO4·2H2O×CEC×ESP×SAR)1/7
(Hazelton et al., 2016)

(3) Soil Fertility Index:

Soil fertility index=(N×P×K×OM)1/4\text{Soil fertility index}=(\text{N}\times\text{P}\times \text{K} \times \text{OM})^{1/4}Soil fertility index=(N×P×K×OM)1/4
(Hazelton et al., 2016)

(4) Soil Quality Index (SQI):

SQI=(SPI×SCI×SFI)1/3\text{SQI}=(\text{SPI}\times\text{SCI}\times\text{SFI})^{1/3}SQI=(SPI×SCI×SFI)1/3

Table (2): Indicators for evaluating and calculating the soil quality index.

Soil properties	Class	Description	Range	Score
Soil Physical index				
Soil texture	1	فائقة الجودة	Clay loam	1
	2	Exellent	Silty clay loam, loam, silty	1.2
	3	Good	Silt loam, clay < 60%	1.4
	4	Moderate	Sandy clay, sandy clay loam,	1.6
	5	Low	Clay > 60%	1.8
	6	Very low	Loamy sand, Sand	2
BD-Bulk density Mg m^{-3}	1	Very low	1.2≥	1
	2	Low	1.4-1.2	1.4
	3	moderate	1.6-1.4	1.6

	4	High			1.8-1.6	1.8
	5	Very high			1.8 ≤	2
Ks-Hydrolic conductivity cm day^{-1}	1	Very low			1-0.05	1
	2	Low			2-1	1.2
	3	moderate			6-2	1.6
	4	High			12-6	1.8
	5	Very high / extremly low			0.05> او 12<	2
Porocity %	1	Low			≤35	2
	2	Moderate			45-35	1.8
	3	Good			55-45	1.5
	4	Very good			65-55	1.2
	5	Exellent			≥65	1
Frag ment Rock %	1	Very stony			>60%	1
	2	stony			20-60	1.5
	3	Bare to few stone			<20	2
Slope %	1	level			<6%	1
	2	Gentl			6-18	1.2
	3	slope			18-35	1.5
	4	Very slope			>35%	2
Soil Chemical Index						
EC dSm^{-1}	1	Very low			0-2	1
	2	Low			2.1-4	1.2
	3	moderate			4.1-8	1.5
	4	High			8.1-16	1.8
	5	Very high			≥16	2
pH	1	Neutral			6.6-7.3	1
	2	Slightly alkaline			7.3-7.9	1.2
	3	Moderately			7.9-8.4	1.5
	4	Stronge			8.4-9.0	2
CaCO$_3$%	1	Very low			<3%	1
	2	Low			3-10	1.2
	3	Moderate			10-25	1.5
	4	High			25-50	1.8
	5	Very high			>50%	2
CaSO$_4$ 2H$_2$O %	1	Very low			<2	1
	2	Low			2-10	1.5
	3	Moderate			10-25	1.8
	4	High			>25	2
ESP	1	Low			5 ≥	1
	2	Moderate			15-5	1.5
	3	High			15 ≤	2
SAR	1	Low			5 ≥	1
	2	Moderate			13-5	1.5
	3	High			13≤	2
Soil Fertility Index						
N$_{available}$ ppm	1	Very high			>120	1
	2	High			100-120	1.2
	3	Moderate			75-100	1.5
	4	Low			30-75	1.8
	5	Very low			30>	2
P$_{available}$ ppm		Soil texture				
		slitly	medium	Heavy		
	1	15	8	5		1
	2	10-15	5-8	3-5		1.5
	3	5-10	3-5	2-3		1.8
	4	5	3	2		2
K Available ppm	1	Very high			180≤	1
	2	High			120-180	1.5
	3	Moderate			60-120	1.8
	4	Low			60 ≥	2
OM %	1	Very high			<3	1
	2	High			3 -2	1.2
	3	Moderate			2-1	1.5

	4	Low	1-0.5	1.7
	5	Very low	≤0.5	2

RESULTS AND DISCUSSION

General Characteristics of the Soils in the Study Area

Chemical Properties:

Soil pH values ranged from 6.70 to 7.70, with an average of 7.17, a standard deviation of 0.26, and a coefficient of variation (CV) of 3.59%. These values indicate a relatively stable soil reaction within the neutral to slightly alkaline range, which is generally suitable for plant growth in arid environments (Brady & Weil, 2019).

Electrical conductivity (EC) exhibited extremely wide variability, ranging from 1.94 to 145.00 dS m^{-1}, with a mean of 40.78 and a high standard deviation (38.16), corresponding to a very high CV of 93.56%. This indicates severe spatial variation in soil salinity, reflecting differences in irrigation water quality, poor drainage, and intense evaporative processes in some locations (FAO, 2022; Qadir et al., 2014).

Calcium carbonate ($CaCO_3$) ranged from 12.50% to 40.50%, with an average of 24.08%, indicating widespread calcareous soils typical of the Lower Euphrates Basin. Gypsum ($CaSO_4 \cdot 2H_2O$) content ranged from 0.06% to 4.86%, with a low mean (0.85%) but a very high CV (135.20%), suggesting highly uneven gypsum distribution across sites (Lal, 2020).

With respect to sodicity indicators, SAR values ranged from 2.18 to 152.07, and ESP ranged from 1.91 to 69.04, with averages of 27.66 and 22.69, respectively. Both indicators exhibited high coefficients of variation (123.39% and 75.48%), indicating substantial spatial variability in sodicity and highlighting that some soils are exposed to hazardous levels of exchangeable sodium, leading to poor structural stability and reduced permeability (Mbarki et al., 2023).

Fertility Attributes:

Total nitrogen (N) ranged from 21 to 385 mg kg^{-1} with a mean of 97.33. Available phosphorus (P) ranged from 3.00 to 39.96 mg kg^{-1} with a mean of 12.86, while available potassium (K) ranged from 39.70 to 855 mg kg^{-1} with a mean of 264.45. These wide ranges are accompanied by high CVs (67.81%, 77.19%, and 63.48%, respectively), indicating significant variability in nutrient availability due to uneven fertilization practices and heterogeneity in land management (Yost & Hartemink, 2019).

Organic matter (OM) ranged between 0.23% and 8.40%, with a mean of 2.24% and a very high CV (78.53%), reflecting the pronounced organic depletion characteristic of arid-region soils and low microbial activity one of the key indicators of soil quality degradation (Borrelli et al., 2020).

Physical Properties:

Soil moisture content ranged from 0.84% to 17.17%, with an average of 4.15%, indicating limited water-holding capacity. Sand content ranged from 30.4% to 93.6%, compared with silt (0.4–56.4%) and clay (0.8–17.6%), confirming the dominance of sandy loam textures characterized by high permeability and wide pore spaces.

Bulk density (BD) ranged from 0.42 to 1.60 Mg m^{-3} with a mean of 1.33 Mg m^{-3}. Total porosity ranged from 39.79% to 66.48%, with an average of 49.38%, indicating moderately coherent soils that are easily friable. Hydraulic conductivity (Ks) showed relative stability, ranging from 4.32 to 4.98 mm h^{-1} with a low CV (2.97%), suggesting uniformity in soil water transmission capacity.

The physical erosion index (EIrom) ranged from 2.34 to 62.00, with a mean of 13.56 and a very high CV (112.43%), reflecting strong spatial variability in wind erosion susceptibility, influenced by topographic gradients and surface cohesion (Le Bissonnais, 1996; Borrelli et al., 2020).

Soil Quality Indicators:

The Soil Physical Index (SPI) exhibited a narrow range (1.42–1.65) with a mean of 1.54 and a CV of 4.26%, indicating relative stability in the overall physical condition of the soils. The overall Soil Quality Index (SQI) ranged from 1.26 to 1.54, with a mean of 1.43 and a standard deviation of 0.07, placing most soils in the moderate quality class. This aligns with the fertility index (SFI = 1.32) and the chemical index (SCI = 1.46), confirming that the soils of the region are generally of moderate quality, tending toward nutrient deficiency, and are highly sensitive to degradation in the absence of sustainable management practices (FAO, 2022; Karlen et al., 2021).

Table (1): Statistical analysis of the physical, chemical and fertility properties of the soil.

Properties	min	max	mean	SD	CV %
p H	6.700	7.700	7.166	0.257	3.591
EC	1.940	145.000	40.783	38.157	93.563
$CaCO_3$	12.500	40.500	24.076	5.115	21.243
$CaSO_4.2H_2O$	0.060	4.860	0.855	1.157	135.206
SAR	2.177	152.069	27.662	34.132	123.393
ESP	1.913	69.044	22.688	17.125	75.479
SCI	1.137	1.669	1.463	0.146	9.997
N	21.000	385.000	97.333	66.001	67.810
P	3.000	39.960	12.862	9.928	77.189
K	39.700	855.000	264.445	167.860	63.476
OM	0.230	8.400	2.237	1.757	78.527
SFI	1.047	1.687	1.320	0.146	11.063
Soil Moisture %	0.840	17.170	4.150	3.093	74.535
Sand	30.400	93.600	62.215	16.080	25.847
Silt	0.400	56.400	31.058	12.974	41.774
Clay	0.800	17.600	6.727	4.465	66.369
BD	0.420	1.595	1.325	0.224	16.868
Porocity	39.793	66.482	49.380	6.351	12.862
Ks	4.323	4.976	4.704	0.139	2.965
EIrom	2.341	62.000	13.562	15.249	112.433
Gravel %	20.000	20.000	20.000	0.000	0.000
SPI	1.418	1.649	1.541	0.066	4.262
SQI	1.260	1.539	1.434	0.070	4.868

Pedological Distribution of Soil Properties in the Study Area

The particle-size distribution of the soils in the study area reflects a sedimentary–climatic regime that explains the dominance of coarse-textured materials at the surface, grading into relatively finer textures with depth. Representative values extracted from the horizons of the described pedons indicate that sand ranges between 25.6–79.6%, silt between 14.4–62.0%, and clay between 1.6–22.0%. This implies that the prevailing surface sequence is generally Sand > Silt > Clay, corresponding to textural classes such as *Loamy Sand* and *Sandy Loam*. In contrast, some subsurface horizons show higher silt than sand (Silt > Sand > Clay), leading to the dominance of *Silt Loam* and *Loam*, as observed in the B and C horizons of several pedons.

A clear pattern of surface salinity appears in Pedon P1, where EC reaches 18.30 dS m^{-1} in the Ap horizon, drops to 8.00 in the Bk horizon, and stabilizes at around 9.90 in the C horizon. This pattern is associated with capillary rise and surface evaporation under arid climatic conditions, whereby salts are transported upward and accumulate progressively over time (Rhoades et al., 1999; Brady & Weil, 2016). In P2, a subsurface salinity peak is evident in the Btk horizon (16.00 dS m^{-1}), compared with 9.25 in Ap and 13.00 in C, indicating a zone of accumulation formed through a combination of limited leaching and the upward movement of base salts, with precipitation near the evaporation–moisture interface behavior typical of calcic accumulation horizons (Btk).

In P3, salinity decreases gradually from 14.60 in the Ap horizon to 10.60 in Bk and 7.56 in C, reflecting a depthward dilution in the absence of distinct salinity barriers. Pedon P4, however, exhibits low salinity at the surface (1.51), with a salinity peak in the Btz horizon (11.98), followed by a decline to 8.23 in C. The “z” suffix denotes the presence of soluble salts or a salt–gypsum crust accumulated in a subsurface position due to water–salt dynamics. In P5, EC values remain relatively low near the surface (5.18–5.29) but increase markedly in C2 (10.80), indicating a deeper saline reservoir that feeds the surface layers during dry periods through capillary rise.

Table 2. Some of Soil properties in study area (soil pedon)

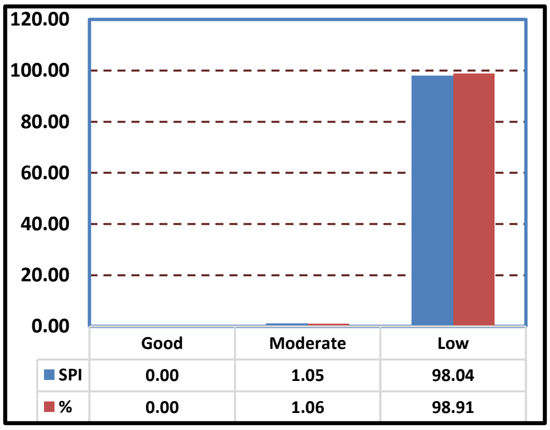
Horizon	**depth cm**	**EC dSm^{-1}**	**pH**	**OM**	**$CaCO_3$**	**Soil texture**			**Texture class**	**SAR**	**Soil classification**
				$gmkg^{-1}$		**clay**	**silt**	**sand**			**USDTAXONOMY**
P1											
Ap		18.30	7.40	20.10	245.00	68.00	232.00	700.00	SL	16.65	Typic Calcids
$B_{(K)}$		8.00	7.80	6.70	280.00	60.00	280.00	660.00	SL	5.23	
C		9.90	7.60	5.10	250.00	156.00	364.00	480.00	L	16.01	
P2											
Ap		9.25	7.00	15.10	245.00	16.00	188.00	796.00	LS	9.98	Claciargids
Btk		16.00	7.20	8.40	300.00	156.00	404.00	440.00	L	17.57	
C		13.00	7.50	3.00	260.00	146.00	374.00	480.00	L	13.97	

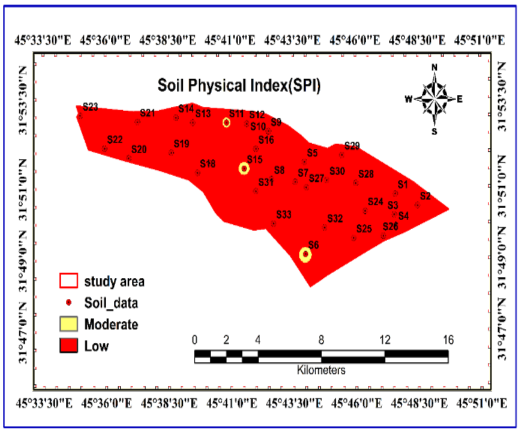
P3										
Ap		14.60	7.40	13.40	245.00	120.00	156.00	724.00	LS	2.82	Calcids
Bk		10.60	7.20	8.40	270.00	100.00	480.00	420.00	L	10.22	
C		7.56	7.30	3.10	230.00	100.00	485.00	415.00	L	3.31	
P4											
A		1.51	7.40	2.34	280.00	116.00	144.00	740.00	SL	3.13	Salinargids
Btz		11.98	7.10	15.10	290.00	184.00	440.00	376.00	L	20.35	
C		8.23	7.50	0.43	265.00	193.00	447.00	360.00	L	5.53	
P5											
Ap		5.18	7.30	2.01	290.00	124.00	372.00	504.00	L	11.42	Haplo Calcids
C1		5.29	7.20	1.84	265.00	124.00	620.00	256.00	SiL	2.51	
C2		10.80	7.20	2.01	280.00	220.00	364.00	416.00	L	14.36	

Indicators of Soil Physical Quality

The results of the Soil Physical Index (SPI) in Dhi Qar Governorate indicate a clear predominance of low physical-quality classes across most of the area. The low class (standard weight = 1.00) dominates the landscape, covering 98.04 km² (98.91%), whereas the medium class (2.00) appears only in limited pockets amounting to 1.05 km² (1.06%). This pattern is attributable to the prevalence of sandy and sandy-loam textures characterized by unstable porosity and low water-holding capacity, in addition to limited organic matter that reduces structural cohesion and increases susceptibility to disintegration and wind erosion (Brady & Weil, 2019; FAO, 2022).

Moreover, the arid climatic conditions in Dhi Qar, marked by repeated wetting–drying cycles, promote the formation of surface crusts after rainfall. These crusts seal fine pores and reduce effective conductivity, thereby increasing surface runoff and soil loss (Le Bissonnais, 1996). Locally elevated bulk density due to compaction further exacerbates this structural weakness by restricting aeration and infiltration, resulting in persistently low SPI values except for a few isolated locations that exhibit slight improvement due to relatively higher organic matter or better-developed structure (Lal, 2020; Karlen et al., 2021).





These findings suggest that the soil's capacity to support seedling establishment and resist erosion remains limited. Improving soil physical quality will require an integrated management strategy that includes increasing organic amendments, minimizing compaction, and adopting conservation agriculture and windbreaks measures that have demonstrated effectiveness in enhancing SPI values in arid and semi-arid environments (Borrelli et al., 2020; FAO, 2022).

If you would like, I can refine the text for journal submission style, adjust citation formatting, or integrate this section within a broader results-and-discussion framework.

Indicators of Soil Chemical Quality

The results of the Soil Chemical Index (SCI) in Dhi Qar Governorate show that most soils fall within the upper levels of this index, reflecting the prevalence of chemical properties that negatively affect soil quality and sustainability. The soils are distributed across two main classes: the medium class (standard weight = 2.00) covers 36.83 km² (37.16%), whereas the high class (3.00) dominates most of the area, amounting to 62.29 km² (62.84%). This distribution is attributed to elevated concentrations of soluble salts, higher levels of calcium carbonate and gypsum, and increased sodicity indicators such as ESP and SAR, all of which contribute to structural degradation and reduced water and air permeability (Richards, 1954; Gupta & Abrol, 1990).

The predominance of the high SCI class across more than two-thirds of the study area indicates that these soils suffer from substantial chemical constraints that impair their fertility and productive capacity. High salt levels disrupt ionic balance and reduce nutrient availability, in addition to negatively affecting seed germination and vegetative growth (Qadir et al., 2007). This chemical pattern is closely linked to the prevailing environmental conditions in Dhi Qar, where arid and semi-arid climates promote salt accumulation due to high evaporation rates and limited leaching. Moreover, irrigation water in many areas contains elevated levels of dissolved salts and calcium, which increases carbonate and gypsum deposition in surface horizons (FAO, 2022).

Recent studies indicate that soils with poor chemical quality are more vulnerable to rapid degradation and desertification if not properly managed, as high salinity and sodicity reduce land productivity and increase reclamation costs (Borrelli et al., 2020; IPCC, 2021). Therefore, the dominance of the high SCI class in Dhi Qar constitutes a clear indicator of environmental fragility and a major agricultural challenge. Effective mitigation strategies include improving irrigation-water quality, applying soil amendments such as agricultural gypsum and organic materials, and enhancing natural and agricultural vegetation cover to limit salt accumulation and restore chemical balance.

These results confirm that SCI serves as a critical diagnostic tool for understanding chemical soil problems and identifying optimal management pathways to ensure agricultural sustainability in arid and semi-arid environments.

Soil Fertility Indicators

The Soil Fertility Index (SFI) values in Dhi Qar Governorate ranged between 1.05 and 1.69, with a mean of 1.32, a standard deviation of 0.15, and a coefficient of variation of 11.06%. This reflects relatively limited variability in fertility levels, though generally tending toward moderate levels. The results indicate that most soils exhibit weak structural cohesion due to the dominance of sandy textures, low organic matter, and sparse vegetation cover factors that reduce nutrient and water retention and increase susceptibility to degradation and desertification (FAO, 2022; Lal, 2004).

Spatially, the moderate class is the most dominant, covering 91.27 km² (92.08%), indicating that most soils fall within a fertility level capable of supporting agriculture if properly managed. In contrast, the poor class accounts for 6.61 km² (6.67%), representing critical low-fertility zones, while the good class is very limited at only 1.26 km² (1.27%).

Low fertility levels are linked to natural and anthropogenic factors. Sandy soils with high permeability exhibit low water and nutrient storage capacity, while sparse vegetation results in insufficient organic matter input organic matter being the principal driver of long-term fertility (Stevenson, 1994). Additionally, some sites polluted with petroleum derivatives may show artificially elevated organic-matter values that do not reflect true fertility improvement but rather chemical contamination that harms microbial activity and nutrient availability (Alloway, 2013).

Thus, the SFI indicates that soils in Dhi Qar are predominantly of moderate fertility but suffer from limited high-fertility areas and notable low-fertility patches, making them vulnerable to degradation and desertification in the absence of sustainable management. Recommendations include enhancing organic content through manure and compost application, adopting crop rotations and leguminous crops to improve nitrogen fixation, and optimizing irrigation management to reduce nutrient leaching (Havlin et al., 2014; Borrelli et al., 2020).

Soil Quality Index

Figure ( ) shows that the Soil Quality Index (SQI) values range between 1.42 and 1.65, with a mean of 1.54, a standard deviation of 0.07, and a coefficient of variation of 4.26%. The soils of the study area exhibit poor structural stability due to the predominance of sandy textures, weak and patchy vegetation cover, and low organic matter. Overall, when calculating the SQI as an aggregate of physical, chemical, and fertility characteristics, the soils fall within the moderate and poor quality classes. The moderate class covers 67.36 km² (67.96%), while the poor class covers 31.76 km² (32.04%).

The SQI clearly reflects the combined influence of physical, chemical, and fertility factors, as well as soil responses to these drivers in arid and semi-arid environments. The classification of soils into moderate and poor quality is closely tied to sandy textures that result in loose, weak structures with low moisture- and nutrient-holding capacity and high erodibility by wind and water (Lal, 2015). Sparse vegetation further limits natural soil protection and reduces organic matter accumulation, which is essential for improving soil structure, nutrient exchange capacity, and microbial activity (Six et al., 2002).

Low organic matter is a key indicator of poor soil quality, as it plays a pivotal role in structural stability, cation-exchange capacity, and long-term fertility (Karlen et al., 2001). The absence of natural organic inputs and weak vegetation render the soils environmentally fragile and poorly responsive to agricultural management.

Soils in the moderate class remain improvable through sustainable practices such as increasing organic inputs, enhancing permanent vegetation cover, and adopting conservation agriculture techniques that reduce soil disturbance and improve moisture retention. In contrast, soils in the poor class present higher risks of degradation and desertification, requiring more intensive protective measures to maintain productivity.

Overall, the SQI results indicate that the soils of the study area are not severely degraded, but they also do not exhibit high-quality characteristics. Rather, they occupy an intermediate stage leaning toward poor quality an environmentally sensitive state that requires targeted management interventions grounded in sustainable soil management principles (Lal, 2015; Six et al., 2002; Karlen et al., 2001).

CONCLUSION

The results of the study showed that the soils of Dhi Qar Governorate are characterized by a clear decline in the quality of their physical properties. The low class of the Soil Physical Index (SPI) dominated most of the study area, accounting for 98.91% of its total area. This reflects the prevalence of sandy textures with weak structure, high bulk density, and low organic matter content, all of which limit the soil's ability to retain water and nutrients. The chemical results also indicated that most soils fall within the high class of the Soil Chemical Index (SCI), representing 62.84%, due to the accumulation of salts and gypsum and the elevated levels of sodicity indicators (SAR and ESP). This points to the influence of the arid climate, saline irrigation water, and the development of secondary salinity.

As for the Soil Fertility Index (SFI), the findings revealed that most soils exhibit moderate fertility (92.08%), indicating limited productive capacity that can be improved through enhanced agricultural management and the addition of organic matter. The Soil Quality Index (SQI) further showed that the majority of soils fall within the moderate-quality class (67.96%), followed by the poor-quality class (32.04%). This reflects the combined interaction of physical, chemical, and fertility characteristics in determining soil efficiency and sustainability.

Overall, the soils of Dhi Qar are environmentally fragile and are affected by multiple natural and human factors, including the arid climate, recurrent drought, salinization, unregulated grazing, and improper tillage. Therefore, they are classified among the sensitive areas prone to degradation and desertification according to the MEDALUS model. The study confirms that integrating field and laboratory analyses with Geographic Information Systems (GIS) constitutes an accurate approach for diagnosing soil degradation, identifying critical zones, and supporting future sustainable land management planning.

RECOMMENDATIONS

There is a need to implement integrated soil management programs focused on improving physical properties through the addition of organic materials and compost to reduce bulk density and increase structural stability and porosity. It is essential to improve irrigation water quality by mixing saline water with better-quality water or by applying microbiological and physical treatment techniques to reduce the accumulation of salts and gypsum on the soil surface. Agricultural gypsum and natural soil amendments should be used to address sodicity and salinity problems, contributing to improved soil structure and enhanced water and nutrient uptake. Conservation Agriculture practices such as reduced tillage, maintaining crop residues on the soil surface, and establishing local windbreaks should be applied to ensure the sustainability of physical properties and to minimize erosion.

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