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Soil Fertility Status and Groundwater Suitability Assessment of Ambach Village(Chikhli Taluka), Navsari District, Gujarat

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ABSTRACT

This study characterized soils and assessed groundwater quality for irrigation in Ambach village, Chikhli taluka, Navsari district. Soil samples from 138 locations at two depths (0-20 cm and 20-40 cm) showed slightly alkaline pH on the surface (6.1-8.9, mean 7.8) and subsurface soils (6.5-8.7, mean 7.9), with 93.78% and 96.94% being non-saline, respectively. The SOC levels in the surface soils were 27.53% low, 36.95% medium, and 35.53% high, while those in the subsurface soils were 40.47% low, 37.70% medium, and 21.83% high. Nitrogen was medium in the surface (284.1-329.5 kg ha^{-1}) and medium to low in the subsurface (239.4-290.2 kg ha^{-1}). The P_2O_5 was high in both layers. K_2O in surface soils was 21.9% low, 24.5% medium, and 53.6% high, whereas the subsurface levels were 26.3% low, 34.0% medium, and 39.6% high. The micronutrients Fe, Mn, Zn, and Cu were mostly high, with the nutrient index indicating high fertility for P_2O_5 and K_2O, however, some areas had medium to low fertility. Groundwater assessment of 60 samples (2023-24) from irrigated fields (417 ha, 57% irrigated) revealed pH 7.4-8.4 (mean 7.8) and EC 0.39-1.74 dS m^{-1} (mean 0.99 dS m^{-1}), with 71.66% classified as high salinity (C3) and 28.33% as medium salinity (C2). SAR ranged from 0.52 to 3.52 (mean 1.33), indicating safe use, while RSC ranged from -0.86 to 7.26 meq L^{-1} (mean 2.61 meq L^{-1}), posing moderate to high alkalinity risks. Gypsum is recommended to mitigate high SAR and RSC. The study addressed challenges such as high soil variability, limited farmer adoption of organic amendments, and poor irrigation water quality (high EC, RSC). It contributed to sustainable agriculture by providing site-specific nutrient management strategies, promoting organic matter incorporation, and recommending efficient soil and water management practices to enhance soil fertility and crop productivity.

Keywords: *Soil characterization, Ambach village, South Gujarat, Agro-climatic zone, Surface and subsurface soil, Soil chemical properties, pH range, Soil organic carbon (SOC), Macronutrient levels (N, P_2O_5, K_2O), Micronutrient levels (Fe, Mn, Zn and Cu), Nutrient Index, Groundwater, pH, EC, SAR, RSC, Gypsum.*

1. INTRODUCTION

The concept of soil quality has evolved since the late 20th century to address concerns about sustainable soil management. Assessing soil fertility in specific areas is vital for sustainable agricultural production. Limited research has explored N, P, and K under different cropping and management systems and their relationships with key properties. Natural variations in major and micronutrient supplies often result in some being sufficient while others are deficient. The effectiveness of chemical fertilizers has declined in recent years due to imbalanced and insufficient use and the low efficiency of inputs in intensive agriculture. Addressing stagnation in crop productivity requires judicious use of macro and micronutrients. Understanding the nutrient status and their relationship with soil properties under different systems is crucial.

This study evaluates the status of major and micronutrients in Ambach village, Chikhli taluka, Navsari district, Gujarat. Classified as sub-humid, the area receives 1864.2 mm of annual rainfall and benefits from canal irrigation (Ukai left bank canal and Keliya dam canal) and substantial groundwater potential. Of the 417 ha of cultivated land, 57% is irrigated 27% via canals and dams, the rest using groundwater and rivers. Groundwater is crucial during dry periods, especially in the monsoon's critical crop growth stages, and for conjunctive use during the Rabi and hot seasons. Groundwater quality was assessed for irrigation purposes, with 60 samples collected from groundwater, rivers, and canals in the village.

2. MATERIALS AND METHODS

Ambach village is located in the Chikhli taluka of Navsari district in Gujarat. It is situated 25km away from the sub-district headquarters of Chikhli and 55km from the district headquarters of Navsari. It falls under the South Gujarat heavy rainfall agro-climatic zone. The crops grown are mainly mango, paddy, sugarcane, sorghum, and vegetables. The total geographical area of the village is 606.06 hectares, of which the total cultivated area is 417 ha, the 14 ha area is pasture and grazing land and the 4 ha area is barren land. The village's major irrigation sources are canals (Ukai and Kakrapar) and bore wells. Out of the total cultivated area, approximately 57.00 per-cent of the area is irrigated and 38.0 per-cent is rainfed.

Using a cadastral map, the village was divided into a 4-ha grid and 276 soil samples (138 at 0-20 cm and 138 at 20-40 cm) were collected.

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Latitude, longitude, and altitude were recorded for each sample point in April-May 2023. To know the interactive effect of pertinent properties, different thematic maps were integrated using GIS-based QGIS 3.22.14- Bialowieza software.

The soil pH was measured in a 1:2.5 soil-to-water suspension using a glass electrode electric pH meter [12], while the electrical conductivity ($EC_{1:2.5}$) of the same suspension was estimated using an electrical conductivity meter [12]. Soil organic carbon was determined using the Walkley and Black rapid titration method [12]. The available nitrogen in the soil was assessed using the alkaline potassium permanganate method [34]. Phosphorus was determined spectrophotometrically following extraction with 0.5 M $NaHCO_3$ at pH 8.5 [22]. Soil available potassium was measured using the flame photometric method after extraction with 1N NH_4OAc [12]. Additionally, DTPA-extractable Fe, Mn, Zn, and Cu were determined from soil samples using an atomic absorption spectrophotometer, following the method suggested by [15].

The total area from which soil samples were collected was divided into 5 areas according to the topography of the village, where out of 276 soil samples, 58, 64, 54, 42, and 58 soil samples were collected from areas 1, 2, 3, 4, and 5, respectively.

Despite access to canal irrigation, some farmers in the selected communities rely on groundwater because of the elevation of their farms above the canal head. During prolonged dry periods, farmers use groundwater, especially during the monsoon when crops were at critical growth stages. Similarly, during the *Rabi* and hot seasons, farmers used groundwater and canals.

A total of 60 groundwater, river, and canal water samples were collected from the selected villages during 2023-24 and analyzed for quality parameters, including $pH_{2.5}$, $EC_{2.5}$, SAR, and RSC, with reference to [29].

3. RESULTS AND DISCUSSION

Soil characteristics

The $pH_{1:2.5}$ of the surface samples ranged from 6.1 to 8.9 with a mean of 7.8, while in the case of subsurface samples, 6.5 to 8.7 $pH_{1:2.5}$ range was recorded with a mean value of 7.9. Based on these $pH_{1:2.5}$ values, the soils of Ambach village were classified as neutral to slightly alkaline, with approximately 70 per cent of the study area characterized as having a slightly alkaline soil reaction. The soil alkalinity was attributed to a high per-centage of base saturation. Similar findings were reported by [4].

The overall $EC_{1:2.5}$ of the surface and subsurface soils was categorized as slightly alkaline. The values ranged from 0.20 to 0.52 dS m^{-1} and 0.19 to 0.38 dS m^{-1} in surface and subsurface soil samples, respectively. The average $EC_{1:2.5}$ values were 0.35 dS m^{-1} for surface soils and 0.27 dS m^{-1} for subsurface soils. Approximately 95 per-cent of the soils in the study area have no problem with soil salinity because of the adequate natural drainage system.

The slight to marginally saline soils in areas 3 and 2 might be due to the accumulation of salts from irrigation water. Similar findings were reported by [14].

SOC content in surface soils ranged from 0.13 to 1.27 per-cent, with an overall mean value of 0.64 per cent. In the subsurface soils, SOC content ranged from 0.03 to 1.91 per cent, with an overall mean value of 0.57 per cent. 27.53, 36.95 and 35.53 per-cent soil surface were recorded as low, medium and high SOC status, respectively. In the case of soil 40.47, 37.70 and 21.83 per-cent soil samples were recorded as low, medium and high categories, respectively. In general, approximately 77 per cent of subsurface soil samples exhibited low to medium SOC status. Organic carbon showed wide variation and the values were found to vary from low to medium in surface horizons, whereas in subsurface horizons, it was low [28]. These findings are corroborated by [9] and [30].

Available major nutrients

In surface soils, the highest available N ranged from 180.3 to 473.5 kg ha^{-1} and with the lowest (116.0-388.9 kg ha^{-1}), with an average 296.1 kg ha^{-1}. In subsurface soils, the highest available N ranges from 133.3-381.2 kg ha^{-1} and the lowest range of 118.4-347.3 kg ha^{-1}, averaging 290.2 kg ha^{-1} and 239.4 kg ha^{-1} respectively. Irrespective of area, available N content was categorized as medium to low in both surface and subsurface soil samples, with distribution per-centages of 71.5 to 28.5 per-cent in surface soils and 57.8 to 42.2 per-cent in subsurface soils. Similar results were reported by [5] and Similar results were reported for soils of the Saurashtra region by [26] in the Gir Somnath district.

In the case of available phosphorus, its concentration in surface soil samples across different grid areas ranged from 99.4 to 207.9 kg ha^{-1}, with an average of 137.1 kg ha^{-1}. Subsurface soil samples exhibited a range of available P_2O_5 from 69.2 to 147.7 kg ha^{-1}, averaging 100.0 kg ha^{-1}. The soil phosphorus status ranged from medium to high. The high available phosphorus content in the soils may be due to excessive use of phosphatic fertilizers and high organic matter content in soil, as reported by [7].

The available K_2O content ranged, from 16.5 to 2190.0 kg ha^{-1}, with a mean value of 372.7 kg ha^{-1}. In subsurface soil samples, available K_2O ranged from 12.1 to 1416.2 kg ha^{-1}, with a mean value of 306.8 kg ha^{-1}. The soils of Ambach village were classified as medium to high in available K_2O status based on the data. The presence of potash-bearing minerals such as feldspar, muscovite, and biotite, which release K_2O upon weathering, likely contributed to the high K_2O status observed. This finding is supported by the results of [6], [1], and [32]. The low availability of K_2O may result from the infrequent or inadequate application of potassic fertilizers due to their high cost and limited awareness of their importance in crop growth. The high calcium concentration in the soil solution phase may also, reduce K uptake by plants, especially in soils containing high amounts of $CaCO_3$ [33].

DTPA-extractable Micronutrients

The available Fe content varied significantly across the study area, ranging from 1.80 to 99.99 mg kg^{-1}, with an overall mean of 29.53 mg kg^{-1} in surface soil samples. The mean values for subsurface soils ranged from 23.20 to 36.04 mg kg^{-1}. Overall, available Fe content in Ambach village soils was predominantly high.DTPA-Fe content showed an irregular trend in soil depth, with surface soils consistently recording the highest values, likely influenced by medium to high levels of soil organic carbon

(SOC) in the surface layers, then, the magnitude started declining slightly in subhorizons with a slightly irregular trend, keeping its variation with $pH_{1:2.5}$ and SOC reported by [31].

The DTPA-extractable Mn contents ranged from 4.48 to 194.20 mg kg^{-1}, with an average of 46.57 mg kg^{-1} in surface soils. In subsurface soils, the available Mn ranged from 4.63 to 222.35 mg kg^{-1}, averaging 43.16 mg kg^{-1}. Regardless of the profile grouping, nearly all areas contained sufficient DTPA-Mn (>10 mg kg^{-1}) in both the surface and subsurface layers. The high Mn levels can be attributed to the low mobility of Mn^{+2} in soils, which facilitates the accumulation of reducible and soluble forms of manganese. Similar findings were noted by [6].

In Ambach village, the available Zn content in the surface soils varied widely, ranging from 0.13 to 5.78 mg kg^{-1}, with a mean value of 1.44 mg kg^{-1}. Subsurface soils ranged from 0.25 to 4.33 mg kg^{-1}, averaging 1.37 mg kg^{-1}. The decrease in Zn content observed in subsurface soils may be attributed to reduced organic matter accumulation in these layers [8], [18]. Similar trends of decreasing extractable Zn content with depth have been reported in other studies [16].

All soil samples were classified as having sufficient DTPA-Cu (>0.4 mg kg^{-1}). The available Cu content varied from 1.13 to 9.41 mg kg^{-1}, with a mean value of 4.65 mg kg^{-1}. In subsurface soils, Cu ranged from 0.53 to 10.05 mg kg^{-1}, averaging 4.26 mg kg^{-1}. The high availability of Cu in soils may be attributed to the use of copper-containing chemicals, primarily fungicides [6]. These results agree with previous studies conducted across eight talukas in the Kheda district, as reported by [24].

Table 1: Range and mean value of $pH_{1:2.5}$ for surface and subsurface soils sample with distribution into the different classes

Profile Number	No. of Samples	Depth (cm)											
		0 - 20						20 - 40					
		Range	Mean	Classes (%)				Range	Mean	Classes (%)			
				A	N	SA	MA			A	N	SA	MA
1	58	6.6-8.7	7.8	0.0	20.7	75.9	3.5	6.6-8.5	7.9	0.0	13.8	82.8	3.5
2	64	6.5-8.4	7.7	0.0	31.2	68.8	0.0	6.6-8.7	7.8	0.0	28.1	68.8	3.1
3	54	7.2-8.9	8.0	0.0	11.1	81.5	7.4	7.1-8.7	8.1	0.0	7.4	88.9	3.7
4	42	6.8-8.2	7.6	0.0	47.6	52.4	0.0	6.6-8.3	7.6	0.0	47.6	52.4	0.0
5	58	6.1-8.2	7.7	3.5	17.2	79.3	0.0	6.5-8.4	7.9	0.0	13.8	82.8	3.5
Overall	**276**	**6.1-8.9**	**7.8**	**0.7**	**25.5**	**71.6**	**2.2**	**6.5-8.7**	**7.9**	**0.0**	**22.1**	**75.1**	**2.8**
A = Slightly Acidic (<6.5), N = Normal (6.5 - 7.5), SA = Slightly alkaline (7.5 - 8.5) and MA = Moderately alkaline (>8.5)													

Table 2: Range and mean value of $EC_{1:2.5}$ (dS m^{-1}) for surface and subsurface soils sample with distribution into the different classes

Profile Number	No. of Samples	Depth (cm)									
		0 – 20					20 - 40				
		Range	Mean	Classes (%)			Range	Mean	Classes (%)		
				NS	SS	MS			NS	SS	MS
1	58	0.07-1.44	0.39	93.10	6.90	0.00	0.04-0.86	0.29	100.00	0.00	0.00
2	64	0.07-1.66	0.34	93.80	6.30	0.00	0.08-0.97	0.27	96.90	3.10	0.00
3	54	0.16-3.79	0.52	88.90	3.70	7.40	0.09-2.79	0.38	92.60	3.70	3.70
4	42	0.04-0.37	0.20	100.00	0.00	0.00	0.04-0.98	0.20	95.20	4.80	0.00
5	58	0.07-1.78	0.33	93.10	6.90	0.00	0.06-0.40	0.19	100.00	0.00	0.00
Overall	**276**	**0.04-3.79**	**0.35**	**93.78**	**4.76**	**1.48**	**0.04-2.79**	**0.27**	**96.94**	**2.32**	**0.74**
NS= Non saline (<1.0 dS m^{-1}), SS= Slightly saline (1.0-2.0 dS m^{-1}) and MS= Marginal saline (2-3 dS m^{-1})											

Table 3: Range and mean value of available organic carbon (OC) %, N (kg ha^{-1}), P_2O_5 (kg ha^{-1}), and K_2O (kg ha^{-1}) of surface and subsurface soils sample with distribution into the different classes

Profile Number	No. of Samples	Depth (cm)									
		0 - 20					20 - 40				
		Range	Mean	Classes (%)			Range	Mean	Classes (%)		
				L	M	H			L	M	H
Organic carbon (OC) %											
1	58	0.24-1.13	0.65	27.59	27.59	44.87	0.13-0.86	0.52	41.38	44.83	13.79
2	64	0.26-0.80	0.51	50.00	40.63	9.38	0.03-1.14	0.49	50.00	37.50	12.50
3	54	0.13-1.23	0.70	25.93	37.04	37.04	0.08-1.91	0.68	25.93	37.04	37.04
4	42	0.15-1.23	0.66	23.81	38.10	38.10	0.13-1.18	0.62	33.33	38.10	28.57
5	58	0.25-1.27	0.70	10.34	41.38	48.28	0.13-0.87	0.52	51.72	31.03	17.24
Overall	**276**	**0.13 - 1.27**	**0.64**	**27.53**	**36.95**	**35.53**	**0.03-1.91**	**0.57**	**40.47**	**37.70**	**21.83**
L= Low (< 0.50 %), M= Medium (0.50 - 0.75 %) and H= High (> 0.75 %)											

N (kg ha^{-1})											
1	58	202.3-467.3	284.1	34.5	65.5	0.0	157.6-387.3	252.5	44.8	55.2	0.0
2	64	180.3-473.5	329.5	28.1	71.9	0.0	133.3-381.0	290.2	28.1	71.9	0.0
3	54	165.4-426.5	293.7	22.2	77.8	0.0	133.3-381.0	261.4	22.2	77.8	0.0
4	42	116.0-388.7	277.4	33.3	66.7	0.0	118.4-347.3	239.4	57.1	42.9	0.0
5	58	169.3-418.7	295.7	24.1	75.9	0.0	149.7-377.1	246.0	58.6	41.4	0.0
Overall	**276**	**116.03-473.54**	**296.1**	**28.5**	**71.5**	**0.0**	**118.38-387.30**	**257.9**	**42.2**	**57.8**	**0.0**
L = Low (<250 kg ha^{-1}), M = Medium (250-500 kg ha^{-1}) and H= High (> 500 kg ha^{-1})											
P_2O_5 (kg ha^{-1})											
1	58	1.7-339.9	104.7	24.1	17.2	58.6	1.3-355.5	77.3	24.1	24.1	51.7
2	64	4.7-1286.2	207.9	9.4	6.3	84.4	3.8-992.8	147.7	12.5	18.8	68.8
3	54	3.8-462.9	99.4	29.6	11.1	59.3	3.2-266.1	69.2	40.7	25.9	33.3
4	42	14.7-375.5	112.2	9.5	23.8	66.7	2.9-260.9	93.0	9.5	33.3	57.1
5	58	36.5-433.8	161.2	0.0	13.8	86.2	16.7-356.1	113.0	17.2	10.3	72.4
Overall	**276**	**1.66-1286.21**	**137.1**	**14.5**	**14.4**	**71.0**	**1.28-992.82**	**100.0**	**20.8**	**22.5**	**56.7**
L=Low (<28 kg ha^{-1}), M=Medium (28 - 56 kg ha^{-1}) and H=High (>56 kg ha^{-1})											
continue table 3											
K_2O (kg ha^{-1})											
1	58	16.5-1745.2	317.3	44.8	20.7	34.5	12.1-1276.6	243.5	44.8	24.1	31.0
2	64	42.4-1236.2	393.7	9.4	25.0	65.6	33.9-1457.9	347.6	12.5	37.5	50.0
3	54	20.4-2190.0	364.0	51.9	11.1	37.0	24.3-1461.2	299.7	59.3	14.8	25.9
4	42	150.9-909.1	367.2	0.0	38.1	61.9	132.0-733.2	319.2	4.8	52.4	42.9
5	58	114.4-880.3	421.1	3.5	27.6	69.0	102.7-690.9	324.1	10.3	41.4	48.3
Overall	**276**	**16.5-2190.0**	**372.7**	**21.9**	**24.5**	**53.6**	**12.14-1461.18**	**306.8**	**26.3**	**34.0**	**39.6**
L = Low (<140 kg ha^{-1}), M = Medium (140-280 kg ha^{-1}) and H= High (>280 kg ha^{-1})											

Table 4: Range and mean value of available micronutrient DTPA-Fe (mg kg^{-1}), DTPA-Mn (mg kg^{-1}), DTPA-Zn (mg kg^{-1}) and DTPA-Cu (mg kg^{-1}) of surface and subsurface soils sample with distribution into different classes

Profile Number	No. of Samples	Depth (cm)									
		0 - 20					20 - 40				
		Range	Mean	Classes (%)			Range	Mean	Classes (%)		
				L	M	H			L	M	H
DTPA-Fe (mg kg^{-1})											
1	58	1.80-88.00	30.63	3.45	6.90	89.66	8.56-84.62	27.83	0.00	17.24	82.76
2	64	2.93-99.99	28.81	9.38	15.63	75.00	3.73-86.12	27.84	6.25	15.63	78.13
3	54	5.91-62.85	23.59	0.00	22.22	77.78	3.93-82.34	23.20	7.41	18.52	74.10
4	42	2.93-75.70	32.33	9.52	0.00	90.48	2.37-88.56	36.04	9.52	4.76	85.71
5	58	7.42-55.81	32.23	0.02	3.44	96.55	5.34-61.39	26.36	0.00	6.90	93.10
Overall	**276**	**1.80-99.99**	**29.53**	**4.47**	**9.64**	**85.89**	**2.37-88.56**	**28.25**	**4.64**	**12.61**	**82.76**
D= Deficit (< 5 mg kg^{-1}), M= Marginal (5-10 mg kg^{-1}) and S= Sufficient (>10 mg kg^{-1})											
DTPA-Mn (mg kg^{-1})											
1	58	10.93-181.75	56.88	0.00	0.00	100.00	10.50-171.45	48.16	0.00	0.00	100.00
2	64	4.48-194.20	49.86	3.13	6.25	90.63	6.46-145.65	42.81	0.00	9.38	90.63
3	54	6.46-154.75	38.80	0.00	18.52	81.48	4.63-99.70	35.73	3.70	11.11	85.19
4	42	6.63-120.35	49.18	0.00	14.29	85.71	6.85-222.35	56.29	0.00	14.29	85.71
5	58	12.58-73.87	38.15	0.00	0.00	100.00	9.53-75.60	32.74	0.00	6.90	93.10
Overall	**276**	**4.48-194.20**	**46.57**	**0.63**	**7.81**	**91.56**	**4.63-222.35**	**43.15**	**0.74**	**8.34**	**90.93**
Continue table 4											
D = Deficit (< 5 mg kg^{-1}), M=Marginal (5-10 mg kg^{-1}) and S=Sufficient (>10 mg kg^{-1})											
DTPA-Zn (mg kg^{-1})											
1	58	0.65-2.13	1.33	0.00	27.59	72.41	0.45-3.23	1.36	3.45	31.03	65.52
2	64	0.24-2.70	1.33	9.38	21.88	68.75	0.26-3.43	1.27	9.38	25.00	65.63
3	54	0.21-5.78	1.60	7.41	18.52	74.10	0.54-3.10	1.38	0.00	29.63	70.37
4	42	0.13-3.03	1.33	4.76	28.57	66.67	0.25-4.33	1.46	4.76	28.57	66.67
5	58	0.55-3.19	1.63	0.00	10.34	89.66	0.65-2.94	1.38	0.00	20.69	79.31
Overall	**276**	**0.13-5.78**	**1.44**	**4.31**	**21.38**	**74.32**	**0.25-4.33**	**1.37**	**3.52**	**26.98**	**69.50**
D= Deficit (<0.5 mg kg^{-1}), M=Marginal (0.5 - 1.0 mg kg^{-1}) and S=Sufficient (>1.0 mg kg^{-1})											
DTPA-Cu (mg kg^{-1})											
1	58	1.60-8.45	4.54	0.00	0.00	100.00	0.53-8.18	3.96	0.00	0.00	100.00
2	64	1.77-8.37	4.41	0.00	0.00	100.00	1.42-8.05	4.19	0.00	0.00	100.00
3	54	1.13-9.41	3.95	0.00	0.00	100.00	1.19-9.00	3.81	0.00	0.00	100.00
4	42	1.95-8.90	5.53	0.00	0.00	100.00	1.62-10.05	5.40	0.00	0.00	100.00
5	58	1.76-8.10	4.82	0.00	0.00	100.00	1.44-6.58	3.92	0.00	0.00	100.00
Overall	**276**	**1.13-9.41**	**4.65**	**0.00**	**0.00**	**100.00**	**0.53-10.05**	**4.26**	**0.00**	**0.00**	**100.00**
D = Deficit (<0.2 mg kg^{-1}), M = Marginal (0.2 - 0.4 mg kg^{-1}) and S = Sufficient (>0.4 mg kg^{-1})											

Nutrient Indices

In surface soils, the Nutrient Index (NI) for Organic Carbon (OC) ranged from high to medium, and available nitrogen (N) had a medium to low NI across all soils, likely due to targeted fertilizer use, continuous cropping, and nitrogen loss from leaching or volatilization. Similar results were reported by [32]. Phosphorus showed high to medium NI, possibly from FYM or phosphatic fertilizers, while potassium had high to medium NI. DTPA-extractable micronutrients (Fe, Mn, Zn & Cu) had high NI in all soils, both surface and subsurface. The high NI values for Fe (2.35), Mn (2.36), and Cu (2.48) in the soils of Jamnagar district was reported by [32].

Table 5: Nutrient Index (NI) of the respective area

Nutrient	Area 1		Area 2		Area 3		Area 4		Area 5	
	0-20 cm	20-40 cm	0-20 cm	20-40 cm	0-20 cm	20-40 cm	0-20 cm	20-40 cm	0-20 cm	20-40 cm
OC	2.17	1.72	1.59	1.63	2.11	2.11	2.14	1.95	2.38	1.66
N	1.66	1.55	1.72	1.72	1.78	1.78	1.67	1.43	1.76	1.41
P_2O_5	2.34	2.28	2.75	2.56	2.30	1.93	2.57	2.48	2.86	2.55
K_2O	1.90	1.86	2.56	2.38	1.85	1.67	2.62	2.38	2.66	2.38
Fe	2.86	2.83	2.66	2.72	2.78	2.67	2.81	2.76	2.97	2.93
Mn	3.00	3.00	2.88	2.91	2.81	2.81	2.86	2.86	3.00	2.93
Zn	2.72	2.62	2.59	2.56	2.67	2.70	2.62	2.62	2.90	2.79
Cu	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00

Correlation matrix

The results revealed that the pH of the surface soil was negatively and significantly correlated with Fe (r=-0.686), Mn (r=-0.685), Zn (r=-0.276) and Cu (r=-0.391). An increase in soil acidity (decrease in soil pH) increases, the availability of micronutrients in cationic forms, such as Fe, Mn, Zn, and Cu, as reported by [23]. In the case of subsurface soils, pH was negatively significantly correlated with P_2O_5 (r=-0.217*), Fe (r=-0.665), Mn (r=-0.698), Zn (r=-0.282) and Cu(r=-0.404). The availability of phosphorus, primarily $H_2PO_4^-$ and HPO_4^{2-} ions, is highly pH-dependent. Its availability in many soils is highest when the pH is neutral or slightly acidic and declines as the soil becomes strongly acidic or strongly alkaline as stated by [23].

The EC of the surface soil was positive and significantly correlated with OC (r=0.207*), N (r=0.226), K_2O (r=0.481), Mn (r=0.278) and Zn (r=0.493). The electrical conductivity was positively correlated with soluble K [27]. In the case of subsurface soils, EC was positively and significantly correlated with N (r=200*), K_2O (r=0.355), Mn (r=0.212*) and Zn (r=0.372).

The organic carbon of the surface soil samples was positively and significantly correlated with N (r=0.317), Fe (r=0.208*), Zn (r=0.475) and Cu (r=0.315). A significant positive correlation (r=0.639) was found between organic carbon and available nitrogen. This relationship was found because most soil nitrogen is in organic form, as reported by [19]. A positive non-significant correlation was recorded with P_2O_5, K_2O and Mn. A non-significant and positive correlation of available P was observed with OC (r=0.0318). This relationship might be due to the presence of more than 50 per-cent of P in organic forms and after the decomposition of organic matter as humus is formed, which forms complex with Al and Fe and that is a protective cover for P-fixation with Al and Fe, thus reducing P adsorption/ fixation reported by Tisdale *et al.* (1985).

Table 6: Simple correlations among different parameters of surface and sub-surface soils

Surface samples (0-20 cm)										
	pH	EC (dS m^{-1})	OC (%)	N (kg ha^{-1})	P_2O_5 (kg ha^{-1})	K_2O (kg ha^{-1})	Fe (mg kg^{-1})	Mn (mg kg^{-1})	Zn (mg kg^{-1})	Cu (mg kg^{-1})
pH	1.000									
EC (dS m^{-1})	-0.031	1.000								
OC (%)	-0.112	0.207*	1.000							
N (kg ha^{-1})	-0.118	0.226**	0.317**	1.000						
P_2O_5 (kg ha^{-1})	-0.155	0.078	0.081	0.158	1.000					
K_2O (kg ha^{-1})	-0.046	0.481**	0.087	0.187*	0.259**	1.000				
Fe (mg kg^{-1})	-0.686**	-0.021	0.208*	0.147	0.224**	-0.015	1.000			
Mn (mg kg^{-1})	-0.685**	0.278**	0.112	0.127	0.131	0.087	0.699**	1.000		
Zn (mg kg^{-1})	-0.276**	0.493**	0.475**	0.297**	0.348**	0.510**	0.425**	0.395**	1.000	
Cu (mg kg^{-1})	-0.391**	-0.056	0.315**	0.212*	0.145	0.038	0.710**	0.406**	0.399**	1.000
Sub-surface samples (20-40 cm)										
pH	1									
EC (dS m^{-1})	0.032	1.000								
OC (%)	0.152	-0.015	1.000							
N (kg ha^{-1})	-0.087	0.200*	-0.055	1.000						
P_2O_5 (kg ha^{-1})	-0.217*	-0.033	-0.043	0.219**	1.000					
K_2O (kg ha^{-1})	0.008	0.355**	-0.065	0.140	0.209*	1.000				
Fe (mg kg^{-1})	-0.665**	0.046	-0.031	0.232**	0.325**	-0.104	1.000			
Mn (mg kg^{-1})	-0.698**	0.212*	-0.064	0.137	0.089	0.002	0.707**	1.000		
Zn (mg kg^{-1})	-0.282**	0.372**	-0.036	0.172*	0.356**	0.310**	0.541**	0.472**	1.000	
Cu (mg kg^{-1})	-0.404**	0.058	-0.041	0.286**	0.215*	-0.018	0.688**	0.420**	0.442**	1.000
**** star and * star denote significant correlation (2-tailed) at 0.01 level and 0.05 level, respectively.**										

Nitrogen showed a positive and significant correlation (r=0.62) with organic carbon, as reported by [21]. In surface soils, Nitrogen was positively and significantly correlated with Zn (r=0.297), K_2O (r=0.187*) and Cu (r=0.212*). In subsurface soils, the correlation of nitrogen was positive and significant with P_2O_5 (r=0.219), Fe (r=0.232), Cu (r=0.286) and Zn (r=0.172*). The K had a significant positive correlation with nitrogen [20]. The same results were recorded by [25].

The phosphorus content of surface soils was positively and significantly correlated with K_2O (r=0.259), Fe (r=0.224) and Zn (r=0.348). In the case of subsurface soils, Phosphorus is positively and significantly correlated with K_2O (r=0.209*), Fe (r=0.325), Zn (r=0.356) and Cu (r=0.215*). P was significantly correlated with available potassium [20].

Potassium was positively and significantly correlated with Zn (r=0.510) and Zn (r=0.310) in surface soils and subsurface soils, respectively.

Fe was positively and significantly correlated with Mn (r=0.699), Zn (r=0.425), and Cu (r=0.710) in the surface soils samples. In the case of subsurface soils samples Fe was positively and significantly correlated with Mn (r=0.707), Zn (r=0.541) and Cu (r=0.688).

Mn was positively and significantly correlated with Zn (r=0.395) and Cu (r=0.406) in the surface soil samples. In the subsurface soil samples, Mn was positively and significantly correlated with Cu (r=0.420) and Zn (r=0.472). Soil micronutrient cations such as Cu and Zn are positively and significantly correlated with available Mn [11].

Zn was positively and significantly correlated with Cu (r=0.399), Cu (r=0.442) in surface soils and subsurface soils, respectively.

Available Fe contents showed positive and significant correlations with pH (r=0.8623), OC (r=0.8355), available N (r=0.8302), available P_2O_5 (r=0.7812) and also positive and significant correlations with other micronutrient cations [2].

The micronutrient cations showed significant and positive correlation coefficients with pH (r=0.8220), OC (r=0.7422), available N (r=0.7590), available P_2O_5 (r=0.7840) and available K_2O (r=0.5161*) reported by [2].

Total Zn exhibited a significant correlation with the total contents of Cu, Mn and Fe contents. This positive association among the micronutrient cations implies that (1) similar factors govern their distribution in soils, (2) soils rich in one of these micronutrients will be rich in the remaining ones, and *vice versa*, as reported by [13].

Quality parameters and classification of groundwater samples

During the pre-monsoon season, the pH of the water samples ranged from 7.4 to 8.4, with a mean value of 7.8, indicating a neutral to alkaline nature. Continuous application without precautions can lead to soil alkalinity issues.

The EC of the water samples ranged from 0.39 dS m^{-1} to 1.74 dS m^{-1}, with a mean value of 0.99 dS m^{-1}. Out of the 60 water samples, 43 were in the C3 (high salinity water) class and 17 were in the C2 (medium salinity water) class, indicating high salinity levels in the study area. Approximately 71.66 per-cent of the samples were classified under the C3 (high salinity water) category, indicating a high salinity problem, while 28.33 per-cent were categorized under C2 (medium salinity water).

Based on the soluble cation content, the SAR and RSC were computed. The SAR during the pre-monsoon season ranged from 0.52 to 3.52, with a mean value of 1.33, placing all samples in the S1 category, and indicating safe irrigation use.

The RSC values of water samples during the pre-monsoon season ranged from -0.86 meq l^{-1} to 7.26 meq l^{-1}, with a mean of 2.61 meq l^{-1}, suggesting a moderate to high risk of alkalinity hazards. The highest RSC value (7.26 meq l^{-1}) indicated potential issues that could increase soil sodicity. The application of gypsum is recommended to mitigate high SAR and improve soil and crop quality. To reduce the high SAR_{iw}, gypsum is the most economical amendment [10]. Neutralizing of RSC in irrigation water through the application of either Gypsum and press-mud, either alone or in combination, significantly improved fodder quality and most of the macro as well as micronutrients in paddy fields, as reported by [17].

Table 7: Quality parameters and classification of ground water samples of Ambach

PN	$pH_{2.5}$	$EC_{2.5}$ (dS m^{-1})		SAR		RSC (meq l^{-1})	
PN 1							
1	7.8	1.02	C3	1.09	S1	3.36	US
2	7.9	1.12	C3	1.85	S1	4.69	US
3	7.9	1.21	C3	1.68	S1	2.71	US
4	7.7	1.06	C3	2.00	S1	3.61	US
5	7.8	1.35	C3	2.59	S1	4.38	US
6	7.6	0.62	C2	0.90	S1	1.69	US
7	7.7	1.16	C3	1.61	S1	2.72	US
8	8.0	1.03	C3	1.46	S1	2.42	US
9	7.9	0.99	C3	1.24	S1	2.59	US
10	8.0	0.50	C2	0.75	S1	0.94	S
11	7.7	1.74	C3	3.63	S1	7.16	US
12	7.8	1.04	C3	1.53	S1	3.43	US
13	7.6	1.13	C3	1.81	S1	3.34	US
PN 2							
1	7.7	1.31	C3	1.29	S1	1.50	US
2	8.0	0.48	C2	1.00	S1	1.66	US
3	7.7	0.71	C2	0.63	S1	1.22	S
4	7.8	1.05	C3	0.77	S1	1.97	US
5	7.7	0.70	C2	0.68	S1	3.77	US
6	7.6	1.09	C3	0.99	S1	1.81	US
7	7.8	1.23	C3	1.21	S1	2.83	US

8	8.1	0.39	C2	0.97	S1	1.25	S
9	7.7	0.70	C2	0.68	S1	3.77	US
10	7.5	1.10	C3	1.28	S1	0.81	S
11	7.4	0.74	C2	0.93	S1	2.63	US
12	7.5	1.29	C3	1.61	S1	3.49	US
13	7.7	0.80	C3	0.80	S1	1.86	US
14	7.5	0.99	C3	1.81	S1	3.88	US
15	8.1	0.90	C3	1.10	S1	2.06	US
PN 3							
1	7.6	1.01	C3	1.82	S1	4.34	US
2	7.7	1.45	C3	2.54	S1	4.65	US
3	7.6	1.02	C3	1.45	S1	3.26	US
4	7.5	1.05	C3	1.19	S1	2.37	US
Continue table 7							
PN 4							
1	7.6	0.78	C3	1.20	S1	4.02	US
2	7.9	0.72	C2	1.20	S1	4.36	US
3	8.0	0.93	C3	1.49	S1	2.29	US
4	8.0	0.84	C3	1.55	S1	1.44	US
5	7.6	1.19	C3	1.01	S1	0.21	S
6	7.8	0.59	C2	0.63	S1	1.41	US
7	7.6	0.64	C2	0.52	S1	1.31	US
8	7.7	1.07	C3	0.78	S1	-0.86	S
9	7.5	1.09	C3	2.28	S1	3.77	US
10	7.9	0.74	C2	0.60	S1	0.99	S
11	8.2	0.44	C2	0.61	S1	0.50	S
PN 5							
1	7.7	1.25	C3	1.88	S1	3.31	US
2	7.8	0.67	C2	0.89	S1	0.81	S
3	8.3	0.58	C2	0.89	S1	0.94	S
4	7.9	0.87	C3	1.25	S1	1.73	US
5	7.6	1.02	C3	1.00	S1	2.58	US
6	7.6	0.78	C3	0.81	S1	2.03	US
7	7.6	0.71	C2	0.82	S1	2.67	US
8	7.5	0.80	C3	0.75	S1	1.60	US
9	7.8	0.76	C3	1.02	S1	3.52	US
10	8.4	0.62	C2	1.90	S1	2.76	US
11	7.7	0.96	C3	1.97	S1	4.22	US
12	7.6	1.30	C3	2.25	S1	3.99	US
13	7.8	0.94	C3	2.22	S1	4.34	US
14	7.6	1.05	C3	1.55	S1	2.82	US
15	7.5	1.09	C3	1.17	S1	2.21	US
16	7.9	1.03	C3	1.39	S1	2.81	US
17	7.5	0.97	C3	1.00	S1	2.59	US
Min	**7.4**	**0.39**		**0.52**		**-0.86**	
Max	**8.4**	**1.74**		**3.63**		**7.16**	
Mean	**7.8**	**0.94**		**1.33**		**2.61**	

4. CONCLUSION

Soils were slightly alkaline with non-saline EC values and organic carbon was medium to low. Nitrogen levels were generally low, phosphorus was high except in area 3, and potassium was high. Fe and Mn concentrations were high except in area 4, Zn concentration was medium to high,and Cu concentration was high. Surface and subsurface soils showed good fertility and slightly alkaline pH. The climate was sub-humid with 1874.4 mm of rainfall, highest in July and temperatures ranging from the lowest in January to the highest in June and April.The study area's soil was overall alkaline, requiring correction with organic manure. For low macronutrient levels, bio-compost and increasing RDF by 10 per-cent were recommended, whereas for high macronutrient level, RDF should be decreased by 10 per-cent. To improve low organic matter content, farmers should advise using FYM, compost, vermicompost, and greenmanuring with the application of essential nutrients with appropriate adjustment for doses based on soil fertility status, which are likely to improve crop performance on a sustainable basis.

Groundwater had high EC and RSC levels, requiring gypsum application with irrigation. In conclusion, while canal irrigation benefits the area, groundwater quality assessments underscore the need for careful management to avoid soil and crop health issues associated with salinity and alkalinity.

Future Scope of the Study

This study paves the way for future research on the long-term effects of organic amendments and nutrient management on soil health and crop productivity. Optimizing organic manure, biofertilizers, and gypsum applications can enhance soil fertility and water quality. Evaluating salt-tolerant rice varieties and microbial inoculants under varying conditions will refine site-specific recommendations.

Additionally, integrating precision agriculture for real-time soil monitoring can boost sustainability. The findings from this survey will serve as a valuable scientific reference for future research on soil and water management in South Gujarat.

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Conflict of interest
The authors declare that they have no conflict of interest.

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