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Assessment of Seasonal Variability in Soil and Groundwater Quality and Antimicrobial Potential of Soil Microbes in the Napasar Region of Bikaner

Bhavna Sharma¹, Dr. Uma Rathore², Dr. Narendar Bhojak³

Research Scholar, Department of Chemistry, M.G.S. University, Bikaner (Raj.), India¹

Associate Professor, Department of Chemistry, Govt. Dungar College, Bikaner (Raj.), India²

Professor, Department of Chemistry, Govt. Dungar College, Bikaner (Raj.), India³

ABSTRACT: Soil and groundwater are crucial resources in arid ecosystems, and their quality directly influences agricultural productivity, ecological balance and human health. The present study investigates the seasonal variability in the physico-chemical characteristics of soil and groundwater, along with the antimicrobial potential of soil microbes in the Napasar region of Bikaner, Rajasthan. Samples were collected during summer, monsoon, and winter seasons to evaluate key parameters including water temperature, turbidity, total suspended solids (TSS), electrical conductivity (EC), soil temperature, and moisture content. The findings of this study emphasize the interconnected nature of soil and groundwater quality, the role of seasonal dynamics in shaping their characteristics and the significance of soil microbial communities as reservoirs of antimicrobial activity.

KEYWORDS: Soil; Groundwater; Quality; Seasonal; Antimicrobial.

I. INTRODUCTION

Groundwater and soil are essential resources that sustain a variety of ecosystems, agricultural activities and human well-being. They are influenced by a range of natural and human-induced factors including as climate change, pollution, urbanisation, and alterations in land use. These forces can greatly change the physicochemical properties of groundwater and soil, which can endanger water security, food production and ecosystem integrity. Comprehending the seasonal fluctuations of groundwater and soil characteristics is essential for efficient resource management, environmental preservation, and sustainable progress [1]. Fluctuations in temperature, precipitation and land use practices can significantly impact hydrological processes, nutrient cycling and pollutant movement in groundwater and soil systems. A thorough evaluation of seasonal changes in physicochemical parameters is crucial for developing well-informed policies to reduce environmental threats and protect ecosystem health. Groundwater and soil are essential elements of land ecosystems, providing crucial supplies that sustain different living forms and ecosystem processes. Groundwater and soil quality and dynamics are crucial for maintaining ecological balance, agricultural output and human well-being. It is crucial to comprehend the physicochemical properties of these environmental systems to evaluate their health, adaptability and susceptibility to environmental shifts [2]. This study aims to examine the physical and chemical characteristics of groundwater and soil. It also examines the antimicrobial potential of soil microbes in the Napasar region of Bikaner, Rajasthan.

II. RESEARCH METHODOLOGY

Following methods were used in the study for sample collection from the study area and their analysis:

Study Area: The research region is situated in agroclimatic zone Ic, which is characterised as Hyper Arid Partially Irrigated Western Plain in Rajasthan. Bikaner district is situated in Northwestern Rajasthan between latitudes 27°11' N to 29°03' N and longitudes 71°54' E to 74°22' E. The Indira Gandhi Nahar Project supplies water for irrigation to the North-Western region of Bikaner. For the last 10-15 years, there has been a lack of canal water delivery in the South-Eastern part of Bikaner. As a result, farmers in the region are choosing to install tube wells and use sprinklers for irrigation more frequently.

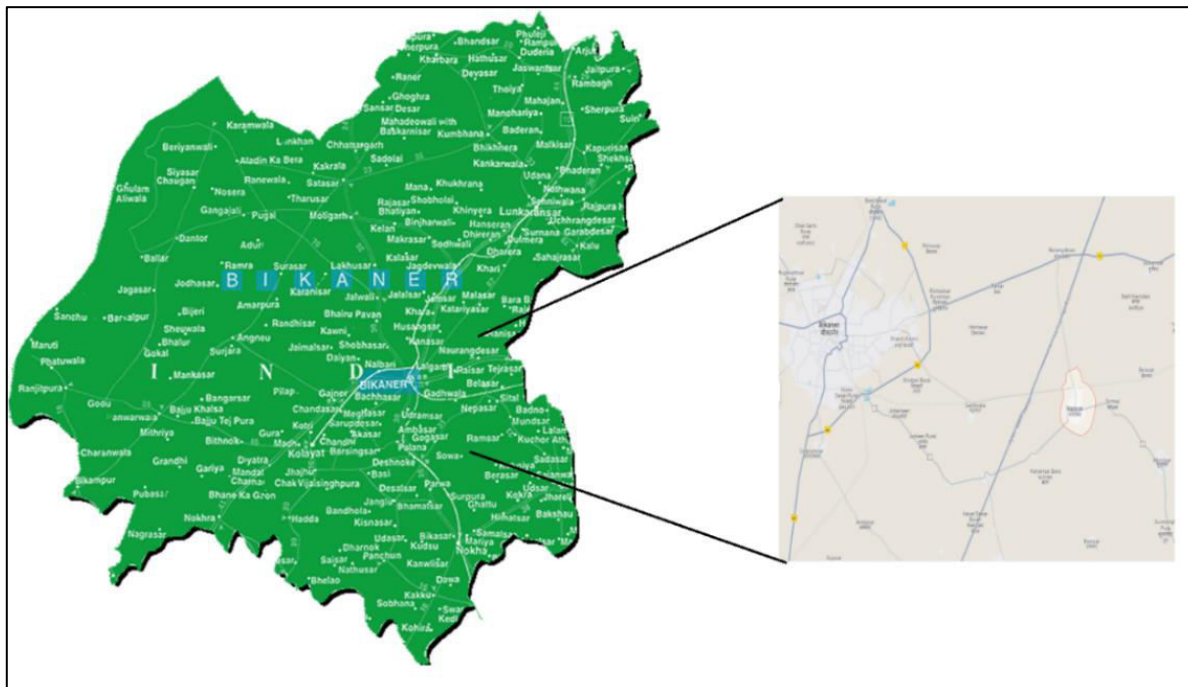


Fig 1: Map of Study Area

Sample Collection: By sampling across different seasons – summer, monsoon, and winter – this study captures the temporal dynamics of physicochemical parameters, allowing for a comprehensive assessment of seasonal variations.

- **Groundwater:** Water samples from different sites were taken in a glass or plastic bottle that had been washed and rinsed with the same water being sampled. Collecting samples was avoided near floating debris or any other contaminants.
- **Soil:** Soil samples gathered underwent laboratory analysis for various soil properties using established methods and protocols.

Physicochemical Parameters: Analytical study includes the assessment of various parameters for soil as well as groundwater. Standardized protocols and calibrated instruments are utilized to maintain consistency and accuracy in data collection. Following parameters are studied:

- **For Soil:** Different parameters were used in case of soil samples collected from different sites. This includes pH [3], Organic Carbon [3], Available phosphorus [3], Micronutrients (Mn, Cu, Fe and Zn) [4], Available potassium [5-6] EC [7], temperature and Total coliform [8].
 - **E.C.:** By using standard digital conductivity meter.
 - **Temperature:** Thermometer.
 - **pH:** Potentiometrically.
 - **Organic Carbon:** Walkley and Black's wet digestion method.
 - **Available Phosphorus:** Using 0.5 molar sodium bicarbonate solution of pH 8.5 as extractant.
 - **Available K:** By flame photometer.
 - **Micronutrients (Mn, Cu, Fe and Zn):** Extract with DTPA and determined by AAS.
 - **Total Coliform:** Lactose broth method.
- **For Groundwater:** Different parameters were used in case of groundwater samples collected from different sites. This includes pH [9], BOD [9], COD, DO [9], Sulphate [9], Chloride [9], Fluoride [9], Mg & Ca [10], temperature, EC, Nitrate [11], TH [12], TSS and TDS [13].
 - **Water Temperature:** Thermometer.
 - **Turbidity:** Nephelometer.

- **EC:** By using standard digital conductivity meter.
- **pH:** Electrometric method.
- **BOD:** Bio assay method.
- **COD:** Dichromate method.
- **Dissolve Oxygen:** Titration with $\text{Na}_2\text{S}_2\text{O}_3$.
- **Nitrate:** Ionometric Method.
- **Total Hardness:** EDTA method.
- **Sulphate:** Spectrophotometric Method
- **Chloride:** Titration with standard AgNO_3 .
- **Mg, Ca:** Titration method.
- **Fluoride:** Ion selective electrode method.
- **TSS, TDS:** Gravimetric method.

Antimicrobial Activity of Soil-Borne Microorganisms: The present investigation was carried out in the Microbiology Laboratory of the University to evaluate the antimicrobial activity of soil-borne microbes against selected pathogenic bacterial strains. The bacterial pathogens used in this study included *Staphylococcus aureus*, *Escherichia coli* and *Bacillus subtilis*, which were obtained from the Microbiology Laboratory of the University.

- **Collection of Soil Samples:** Soil samples were collected from five distinct sites (Site 1 to Site 5) located in Napasar, Bikaner. Samples were collected aseptically in sterile bottles and immediately transported to the laboratory, where they were stored at room temperature until further processing.
- **Isolation and Characterization of Soil Microbes:** The collected soil samples were processed for microbial isolation using standard microbiological procedures. Pure cultures were obtained and characterized based on colonial morphology, cellular morphology, Gram's staining reaction, motility test and biochemical tests.
- **Preparation of Soil Bacterial Metabolites:** To prepare microbial metabolites, two sterile test tubes containing Luria–Bertani (LB) broth were used. One tube was inoculated with soil, the second was left uninoculated to serve as a control for contamination. All tubes were incubated at 37 °C for 24 hours.
- **Antimicrobial Activity Assay:** The antimicrobial activity of soil metabolites was assessed using the agar well diffusion method (Soil Sprinkle Method). For this, sterile Petri plates containing solidified nutrient agar were prepared. Wells were aseptically created in the agar using a sterile cork borer. Pathogenic bacterial strains (*S. aureus*, *E. coli*, and *B. subtilis*) were inoculated into LB broth and then spread uniformly onto the surface of the nutrient agar plates. Samples were dispensed into the wells. The plates were then incubated at 37 °C for 24 hours.
- **Observation of Zone of Inhibition:** Following incubation, antimicrobial activity was determined by measuring the diameter of the zones of inhibition that developed around the wells, indicating the effectiveness of soil-borne microbial metabolites against the tested pathogens.

III. RESULT AND DISCUSSION

The study conducted a comprehensive assessment of the physical and chemical characteristics of groundwater and soil across summer, monsoon, and winter seasons. These parameters highlight the seasonal variability in environmental conditions and their implications for ecosystem functioning, water quality, and soil health. In groundwater, the water temperature followed a clear seasonal pattern: highest in summer (25.4–28.6 °C), moderate in monsoon (23.03–25.09 °C), and lowest in winter (16.2–18.4 °C). Such fluctuations directly influence aquatic ecosystems by regulating metabolic activity and chemical processes. Electrical conductivity (EC) values were highest in winter (1321.8–1381.3 $\mu\text{S}/\text{cm}$), moderate in summer (1222.7–1296.2 $\mu\text{S}/\text{cm}$), and lowest in monsoon (938.6–992.5 $\mu\text{S}/\text{cm}$), reflecting the seasonal availability and concentration of dissolved ions. Turbidity was relatively higher in monsoon (85.2–90.5%) compared to summer (92.8–96.5%) and winter (92.8–94.1%), indicating enhanced soil erosion and runoff during rainy conditions. Total suspended solids (TSS) varied narrowly across seasons but showed the highest concentrations during monsoon (5.25–5.30 mg/L) and summer (4.10–4.43 mg/L), with reduced levels in winter (3.00–3.59 mg/L), suggesting seasonal sediment load variations.

Table 1: Groundwater – Physical Parameters Across Seasons

Site	Temperature (°C)			Turbidity (%)		
	S	M	W	S	M	W
Site 1	26.2	23.03	16.8	92.8	85.2	93.3
Site 2	28.6	24.04	16.2	94.7	89.3	94.1
Site 3	27.9	24.06	18.4	96.5	90.5	93.6
Site 4	25.4	25.09	17.1	93.5	90.4	92.8
Site 5	26.9	24.08	16.9	94.2	89.9	93.3
Mean	27	24.06	17.08	94.34	89.06	93.4
Site	TSS (mg/l)			EC (µS/cm)		
	S	M	W	S	M	W
Site 1	4.20	5.25	3.59	1222.7	945.7	1345.7
Site 2	4.10	5.27	3.20	1256.4	955.6	1365.4
Site 3	4.11	5.26	3.22	1266.5	987.2	1347.5
Site 4	4.22	5.28	3.10	1286.3	992.5	1381.3
Site 5	4.43	5.30	3.09	1296.2	938.6	1321.8
Mean	4.21	5.27	3.15	1265.62	963.92	1352.34

*S=Summer; M=Monsoon; W=Winter

In soil, seasonal differences were also evident. Soil temperature peaked during summer (43–44 °C), dropped during monsoon (38–39 °C), and remained moderate in winter (36–37 °C). Moisture content showed the opposite pattern, being lowest in summer (5.6–8.6%), moderate in winter (5.6–8.6%), and relatively higher in monsoon (4.6–8.6%) due to rainfall recharge. Electrical conductivity (EC) in soil was highest in winter (0.30–0.75 dS/m), moderate in summer (0.20–0.41 dS/m), and lowest in monsoon (0.15–0.29 dS/m), indicating seasonal leaching and accumulation of salts.

Table 3: Soil – Physical Parameters Across Seasons

Site	E.C. (dS/m)			Temperature (°C)			Moisture Content (%)		
	S	M	W	S	M	W	S	M	W
Site 1	0.33	0.20	0.20	37	44	38	7.4	5.8	8.6
Site 2	0.30	0.26	0.25	36	43	39	7.8	5.6	4.6
Site 3	0.65	0.25	0.15	36	43	39	5.6	7.4	5.7
Site 4	0.58	0.41	0.21	37	44	38	8.6	6.5	6.5
Site 5	0.75	0.36	0.29	36	43	39	7.6	8.6	5.5
Mean	0.522	0.296	0.22	36.4	43.4	38.6	7.4	6.78	5.78

*S=Summer; M=Monsoon; W=Winter

The analysis of groundwater quality across summer, monsoon, and winter seasons in the Napasar region revealed notable seasonal variations influenced by climatic conditions, recharge, and anthropogenic activities. In summer, groundwater was distinctly alkaline (pH 8.2–8.9, mean 8.58) with relatively high TDS (868–880 mg/l, mean 874.6 mg/l) and moderate hardness (95–102 mg/l). Dissolved oxygen (DO) remained high (8.2–8.9 mg/l), indicating good aeration, while BOD (5.2–5.9 mg/l) and COD (65–78 mg/l) suggested moderate organic and chemical pollution, possibly from agricultural and domestic sources. Fluoride exceeded the permissible limit (1.1–1.8 ppm, mean 1.42 ppm) at some sites, raising concerns of fluorosis risk. Nitrates (22–27 ppm) and chlorides (48–53 ppm) were within safe limits but reflected agricultural runoff and mineral accumulation due to evaporation. In monsoon, dilution from

rainfall reduced TDS (697–710 mg/l) and hardness (87–92 mg/l), while pH dropped slightly (7.4–8.6, mean 7.92). DO remained high (3.5–4.2 mg/l), and BOD values were similar to summer (2.8–4.1 mg/l). COD (53–58 mg/l) was lower than summer, but nitrate (25–30 ppm) and sulphate (51–58 mg/l) levels rose, likely due to fertilizer leaching. Fluoride averaged slightly higher (1.3–1.8 ppm, mean 1.56 ppm), exceeding safe limits at some sites. Chloride values decreased (29–35 ppm) due to dilution. Overall, monsoon water quality reflected runoff-driven recharge with increased nutrient leaching. In winter, groundwater showed the best quality, with near-neutral pH (6.35–7.58, mean 7.22) and the lowest TDS (492–497 mg/l, mean 494.8 mg/l). DO remained favorable (3.5–4.1 mg/l), while BOD (2.4–2.9 mg/l) and COD (41–49 mg/l) were significantly lower, indicating minimal organic contamination. Hardness was moderate (81–89 mg/l), and nitrates (20–25 ppm), sulphates (41–48 mg/l), and chlorides (23–34 ppm) showed reduced concentrations. Calcium (14.7–17.3 ppm) and magnesium (4–9 ppm) were lower than in other seasons, reflecting reduced leaching. Fluoride values (1.1–1.7 ppm, mean 1.38 ppm) were within or near permissible limits, though some sites remained at risk.

Table 4: Groundwater - Chemical Parameters across Seasons

Site	pH			DO (mg/l)			BOD (mg/l)			COD (mg/l)		
	S	M	W	S	M	W	S	M	W	S	M	W
Site 1	8.6	7.5	7.58	3.5	4.9	3.6	3.5	5.3	2.9	78	56	49
Site 2	8.4	8.6	7.56	4.1	4.8	3.2	4.1	5.6	2.6	75	58	47
Site 3	8.8	7.7	6.35	3.8	4.6	3.5	2.8	5.8	2.4	68	53	45
Site 4	8.9	7.4	7.25	4.2	3.9	3.5	2.9	5.1	2.7	65	56	41
Site 5	8.2	8.4	7.36	3.9	4.2	3.2	2.8	5.9	2.4	76	57	42
Mean	8.58	7.92	7.22	3.9	4.4	3.4	3.2	5.54	2.6	72.4	56	44.8
Site	Hardness (mg/l)			Nitrate (ppm)			Sulphate (mg/l)			Mg (ppm)		
	S	M	W	S	M	W	S	M	W	S	M	W
Site 1	97	88	87	22	26	22	47	56	45	10	11	5
Site 2	99	90	86	25	28	20	45	53	48	12	9	6
Site 3	95	87	89	23	27	23	50	58	43	11	12	8
Site 4	102	92	85	27	25	25	41	51	41	15	13	4
Site 5	100	91	81	26	30	24	43	52	46	14	10	9
Mean	98.6	89.6	85.6	24.6	27.2	22.8	45.2	54	44.6	12.4	11	6.4
Site	Chloride (ppm)			Calcium (ppm)			Fluoride (ppm)			TDS (mg/l)		
	S	M	W	S	M	W	S	M	W	S	M	W
Site 1	49	31	23	22.09	23.09	16.4	1.1	1.6	1.1	875	700	494
Site 2	48	29	28	24.03	25.06	15.9	1.8	1.3	1.5	879	705	492
Site 3	52	34	31	22.08	24.07	14.7	1.4	1.8	1.4	871	697	495
Site 4	50	32	30	25.04	22.04	16.5	1.6	1.5	1.7	868	699	497
Site 5	53	35	34	24.07	20.8	17.3	1.2	1.6	1.2	880	710	496
Mean	50.4	32.2	29.2	23.46	23.01	16.16	1.42	1.56	1.38	874.6	702.2	494.8

*S=Summer; M=Monsoon; W=Winter

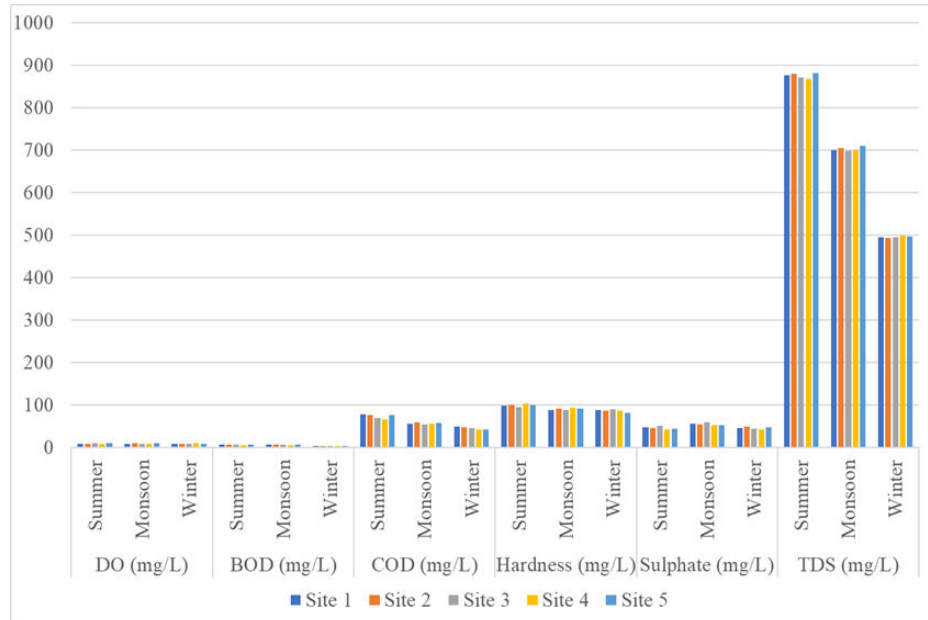


Fig 2: Groundwater - Chemical Parameters (DO; BOD; COD; Hardness; Sulphate; TDS) Across Seasons

The soil analysis revealed significant seasonal variations in fertility and nutrient availability, influenced by climatic conditions, organic matter input, and soil chemical processes. In the summer season, soils were moderately to strongly alkaline (pH 7.89–8.65, mean 8.36) with very low organic carbon (0.05–0.20%, mean 0.096%), indicating poor organic matter status. Phosphorus levels were low to moderate (16–32 Kg/ha), while potassium was high (325–505 Kg/ha), ensuring sufficient K supply. Zinc (0.54–1.89 ppm) and manganese (0.46–1.85 ppm) showed deficiencies at some sites, largely due to high pH reducing availability. Iron (6.48–9.08 ppm) and copper (0.25–0.48 ppm) were generally adequate, though their uptake may be restricted by alkalinity. Overall, soils in summer reflected low fertility potential, especially due to low organic matter and micronutrient constraints.

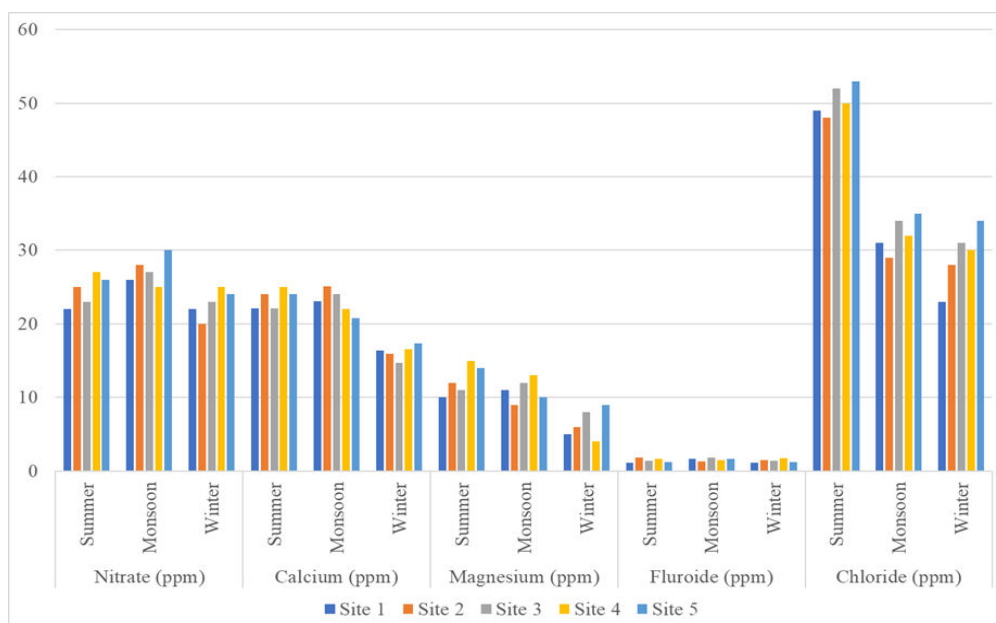


Fig 3: Groundwater - Chemical Parameters (Nitrate; Calcium; Magnesium; Fluoride; Chloride) Across Seasons

During the monsoon season, soil conditions improved due to rainfall and organic matter input. pH remained alkaline (7.85–8.85, mean 8.19), but organic carbon increased significantly (0.16–0.84%, mean 0.496%). Phosphorus levels improved (19–36 Kg/ha), and potassium decreased moderately (156–287 Kg/ha, mean 227.2 Kg/ha), likely due to leaching. Zinc (0.64–2.06 ppm) and iron (7.08–9.86 ppm) showed adequate availability, while copper was low (0.16–0.41 ppm, mean 0.26 ppm), indicating potential deficiency. Manganese (0.45–1.06 ppm) was mostly sufficient, supported by moisture-driven solubilization. Thus, monsoon soils showed improved fertility with better organic matter and micronutrient status, but copper deficiency remained a concern. In winter, soils remained alkaline (pH 7.69–8.66, mean 8.26) with moderate organic carbon (0.15–0.50%, mean 0.332%). Phosphorus levels were moderate to good (22–34 Kg/ha, mean 28.2 Kg/ha), while potassium was high (258–498 Kg/ha, mean 411.8 Kg/ha), reflecting minimal leaching. Zinc (0.27–2.26 ppm) showed variability, with some sites deficient. Iron (6.23–9.45 ppm) and copper (0.28–0.81 ppm, mean 0.532 ppm) were adequate overall, while manganese (0.63–1.75 ppm) remained sufficient, though site-specific differences persisted. Winter soils thus offered better nutrient reserves, especially for potassium and copper, but zinc deficiency was observed in several locations.

Table 5: Soil - Chemical Parameters Across Seasons

Site	pH			Org C (%)			Avail. P (Kg/ha)			Avail. K (Kg/ha)		
	S	M	W	S	M	W	S	M	W	S	M	W
Site 1	7.89	7.85	7.69	0.08	0.47	0.26	23	29	34	505	287	258
Site 2	8.25	8.02	8.22	0.06	0.16	0.3	20	30	30	325	257	365
Site 3	8.45	8.17	8.3	0.05	0.45	0.15	16	36	27	356	249	461
Site 4	8.65	8.07	8.45	0.09	0.84	0.45	21	24	28	425	187	477
Site 5	8.55	8.85	8.66	0.2	0.56	0.5	32	19	22	326	156	498
Mean	8.358	8.192	8.264	0.096	0.496	0.332	22.4	27.6	28.2	387.4	227.2	411.8
Site	Zn (ppm)			Fe (ppm)			Cu (ppm)			Mn (ppm)		
	S	M	W	S	M	W	S	M	W	S	M	W
Site 1	1.89	2.06	2.26	6.48	9.86	9.15	0.25	0.36	0.37	0.99	0.87	0.99
Site 2	0.56	0.98	0.81	8.19	7.08	8.26	0.45	0.16	0.45	0.97	0.98	0.97
Site 3	0.89	0.86	0.63	9.08	9.04	6.23	0.48	0.17	0.81	0.46	0.45	0.89
Site 4	0.54	0.64	0.27	7.55	7.68	7.64	0.26	0.2	0.75	1.85	1.06	1.75
Site 5	0.96	0.87	0.79	9.06	9.15	9.45	0.48	0.41	0.28	0.47	0.87	0.63
Mean	0.968	1.082	0.952	8.072	8.562	8.146	0.384	0.26	0.532	0.948	0.846	1.046

*S=Summer; M=Monsoon; W=Winter

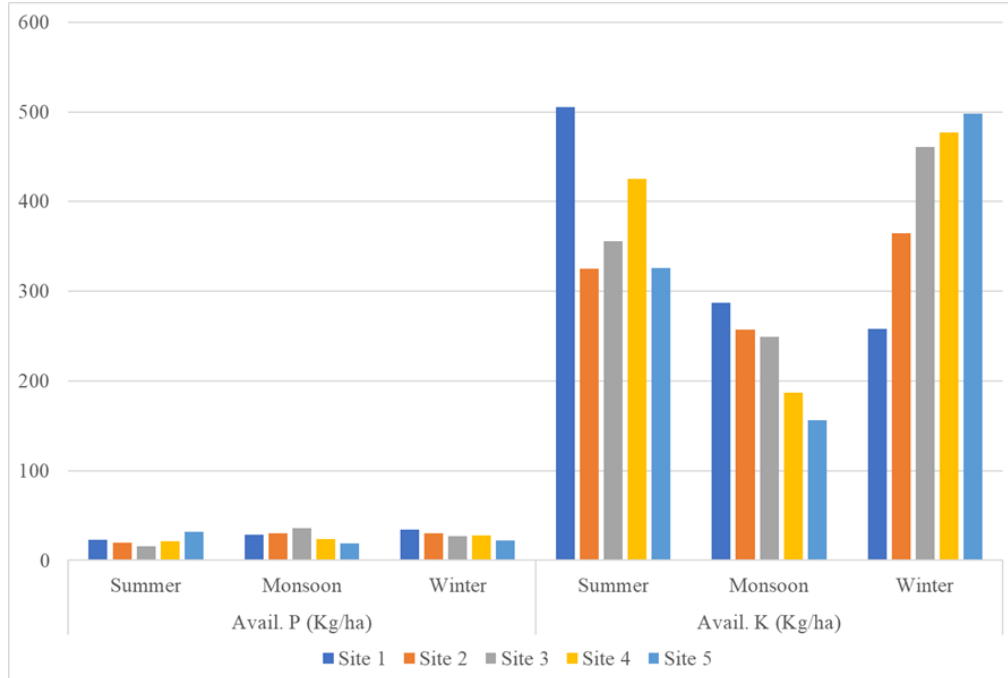


Fig 4: Soil - Parameters (Avail. P.; Avail. K.) Across Seasons

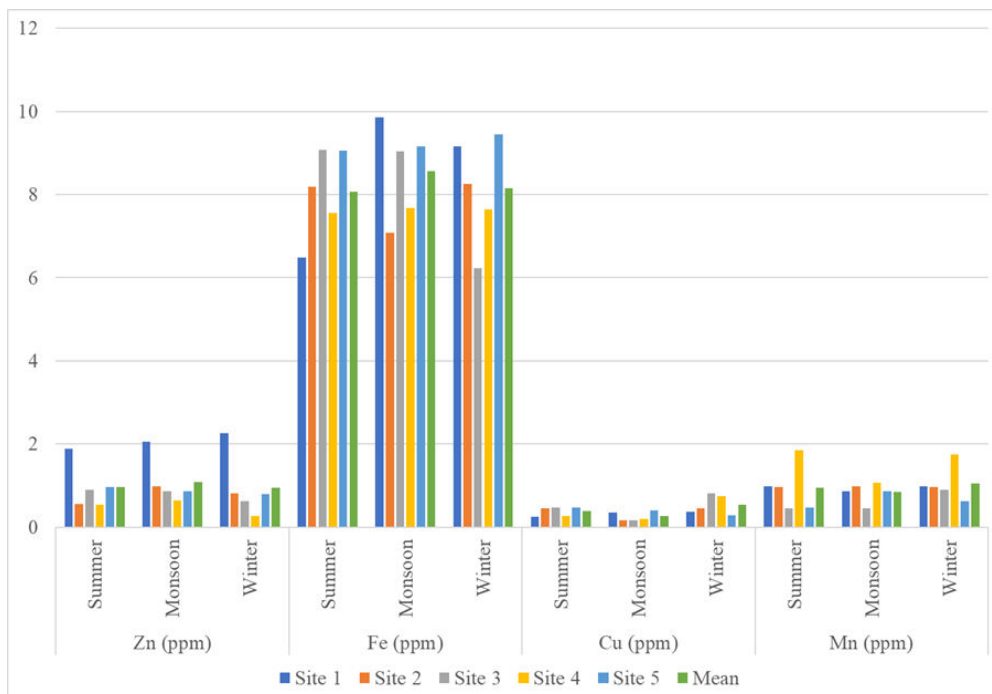


Fig 5: Soil - Parameters (Zn; Fe; Cu; Mn) Across Seasons

Soil samples were collected from the study sites to evaluate their antimicrobial potential against three pathogenic bacterial strains, namely *Escherichia coli*, *Bacillus subtilis* and *Staphylococcus aureus*. The soil samples were inoculated into sterile nutrient broth and incubated at 37 °C for 24 hours. Following incubation, 100 µL of each soil culture was transferred into sterile Eppendorf tubes using a micropipette and centrifuged at 100 rpm for 5 minutes. The

supernatant obtained after centrifugation was applied in two varying volumes onto Petri plates containing the test bacterial organisms. These plates were incubated at 37 °C for 24 hours, after which the antimicrobial activity was assessed by observing and measuring the zones of inhibition formed around the inoculated wells, indicating the presence of bioactive soil microbes.

The antimicrobial activity of soil samples collected from five different sites in Napasar (Bikaner) was assessed against three pathogenic bacterial strains. The results revealed no antimicrobial potential among different sites as well as across different microbial species. The lack of activity may be due to the absence of specific metabolites effective against these pathogens or due to the high resistance of these strains against naturally occurring soil antimicrobials. Overall, the study demonstrates that soil microorganisms from Napasar soils possess no antimicrobial potential. The absence of inhibition indicates that soil-derived antimicrobials in this region may have limited spectrum activity.

Table 6: Antimicrobial activity of soil from different study sites against test organisms

S. No.	Test organisms	Site - 1	Site - 2	Site - 3	Site - 4	Site - 5
1	<i>E. coli</i>	-	-	-	-	-
2	<i>B. subtilis</i>	-	-	-	-	-
3	<i>S. aureus</i>	-	-	-	-	-

The present study on soils of Napasar (Bikaner) revealed that the soils were predominantly loamy sandy in texture, non-saline (EC: 0.22–0.522 dS/m), alkaline in reaction (pH: 8.192–8.358) and generally low in organic carbon content (<0.5% except in monsoon). These findings are in broad agreement with earlier studies conducted in the Bikaner region, which also reported sandy to loamy sand textures, alkaline soil reaction and poor organic matter status. For instance, **Parihar and Choudhary (2017)** noted sandy loam soils with EC ranging from 0.17–0.77 dS/m and pH between 7.11 and 8.75, which closely match the EC and alkaline pH values obtained in the present study [14]. They also highlighted seasonal variations in EC and phosphorus content, which corroborates our finding that phosphorus and potassium levels remained consistently high across seasons in Napasar. Similarly, **Bhunwal et al. (2023)** observed loamy sand to sandy soils in Bikaner with alkaline pH and low organic carbon, attributing these characteristics to the arid climate and calcareous soil parent material [15]. This aligns well with our results, where organic carbon levels were low (0.096–0.496%) except during monsoon. Their observation of medium to sufficient phosphorus and potassium also supports our findings of elevated P (22.4–28.2 kg/ha) and K (227.2–411.8 kg/ha) values, suggesting a regional pattern of nutrient sufficiency in these macronutrients. **Dular and Solanki (2022)** reported that soil properties varied depending on irrigation practices, with canal-irrigated areas exhibiting higher EC and nutrient levels [16]. Although our study sites in Napasar were not explicitly classified by irrigation type, the observed nutrient enrichment in phosphorus and potassium is consistent with their conclusion that inorganic fertilization and irrigation inputs enhance soil fertility. Interestingly, while they found greater organic carbon in non-canal irrigated soils, our study revealed consistently low organic carbon, except during monsoon, indicating the influence of seasonal rainfall rather than irrigation alone in replenishing soil organic matter. In relation to micronutrients, the present study revealed that Zn (0.952–1.082 ppm) and Cu (0.26–0.532 ppm) were mostly within acceptable BIS ranges, Fe (8.072–8.562 ppm) was consistently above the standard and Mn (0.846–1.046 ppm) remained below the critical limit. These results partly align with the findings of **Parihar and Choudhary (2017)**, who reported variable micronutrient distribution with Zn, Fe, Cu and Mn strongly influenced by soil depth and vegetation [14]. Our observation of low Mn levels concurs with their conclusion that sandy loam soils of arid zones often exhibit deficiencies in specific micronutrients. Similarly, **Dular and Solanki (2022)** observed variability in Zn, Fe, Cu and Mn across different sites, supporting the site- and season-dependent nature of micronutrient availability that we observed in Napasar [16]. The work of **Dular and Kanchan (2022)** also supports our results by emphasizing the alkaline pH (8.45–9.15) and poor organic carbon status (0.10–0.21%) of Bikaner soils, which were closely comparable to our recorded values (pH: 8.192–8.358; OC: 0.096–0.496%) [17]. Their observation of very high pH values further validates our finding that alkalinity is a persistent challenge in the soils of Napasar and surrounding regions.

Furthermore, the groundwater samples from Napasar revealed notable seasonal variations in their physicochemical characteristics, with several parameters exceeding the permissible limits set by BIS standards. Our groundwater analysis from Napasar revealed seasonal fluctuations with several parameters exceeding BIS limits, aligning closely

with earlier studies in the Bikaner region. High turbidity, TSS, EC, TDS and fluoride levels in our samples indicate compromised potability, similar to **Sharma et al. (2022)**, who also reported high salinity and TDS in post-monsoon periods, rendering groundwater unsuitable for direct consumption [18]. Consistent with **Kaur and Singh (2009)**, our findings of elevated TDS highlight reduced water clarity and oxygen solubility, which can affect both quality and health [19]. Fluoride levels in our study, particularly during monsoon (1.56 ppm), corroborate the results of **Modi and Soni (2023)**, who documented widespread fluoride contamination in Kolayat and Nokha leading to risks of dental and skeletal fluorosis [20]. **Godara (2017)** also emphasized the deteriorating groundwater quality across Bikaner due to over-extraction, which explains the elevated salinity and alkalinity seen in our summer samples (EC: 1352.34 dS/m, pH: 8.58) [21]. Similarly, **Saran et al. (2023)** noted high EC and brackish nature of groundwater near mining areas, paralleling our observations of mineral enrichment and elevated dissolved solids [22]. However, our results also showed several favorable parameters—BOD, COD, nitrates, sulphates, calcium, magnesium and chlorides—remaining within BIS limits, suggesting moderate organic pollution and low risk of chemical contaminants, unlike some highly impacted industrial and mining zones reported by **Saran et al. (2023)** [23]. Unlike **Kaur and Singh (2009)**, who observed widespread hardness-related health issues, our samples were only moderately hard (85.6–98.6 mg/L), well below the hardness category reported in their study [19]. Also, in our study, the antimicrobial activity of soil extracts from five sites in Napasar was evaluated against selected pathogenic bacterial strains. The results revealed no inhibitory activity, both across test organisms and between sites. This suggests that the soil microbial metabolites in the region lack effective compounds to suppress these pathogens.

IV. CONCLUSION

The present study highlights that the soils of Napasar, much like other parts of Bikaner district, are sandy to loamy sand in texture, alkaline in reaction and generally poor in organic carbon, yet relatively enriched in phosphorus and potassium. Micronutrient availability is uneven, with iron enrichment and manganese deficiency being consistent characteristics, while seasonal rainfall, particularly during the monsoon, enhances organic matter and nutrient status. These features reaffirm the typical fertility constraints and partial advantages of arid-zone soils, where soil quality is largely governed by irrigation practices, rainfall variability and water availability. Similarly, groundwater in the region reflects the broader hydrochemical stress observed in arid Rajasthan, being marked by high salinity, elevated TDS and excess fluoride. Seasonal variations add further complexity, with summer aggravating salinity and TDS problems and monsoon contributing to turbidity and fluoride enrichment. Such conditions place Napasar groundwater within the category of poor drinking water suitability, in agreement with earlier regional studies and point to the need for interventions like rainwater harvesting, desalination and fluoride mitigation. Overall, the findings establish that soil and water resources of Napasar face structural and seasonal limitations typical of arid-zone ecosystems. The combined challenges of low soil fertility, groundwater salinity and fluoride stress and microbial contamination necessitate integrated management approaches, including sustainable irrigation practices, soil fertility enhancement, safe drinking water interventions and continuous monitoring to ensure long-term resource sustainability and public health protection.

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