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Physicochemical and Bacteriological Assessment of some Groundwaters in Al-Khoarah, Rabigh Governorate, Makkah Province, Saudi Arabia

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ABSTRACT

Before using well water for human health maintenance, its quality and compatibility for human and agricultural consumption require regular evaluation. Thus, ten water samples were collected from ten wells scattered in the area of Al-Khoarah of Rabigh, Makkah Province, Saudia Arabia. Samples were analyzed for physical, chemical, and microbiological parameters, including salinity, pH, dissolved oxygen, total dissolved solids (TDS), electrical conductivity (EC), anions (F^{-1}, NO_3^{-1}, SO_4^{-2}, Cl^{-1}), Cations (K^+, Na^+, Mg^{2+}, Ca^{2+}) and heavy metals (Cr, Cd, Be, Ba, As, Al, Ag, Zn, Sb, Se, Pb, Hg & Cu). In addition, bacteriological assessment (Total coliform bacteria, fecal coliform bacteria & total bacterial count) was addressed in this study. The physical, chemical, and microbiological analyses were compared to the standards of the World Health Organization, the Saudi Standards Organization (SASO), and the Gulf Cooperation Council (GCCS). Following WHO guidelines, the total hardness, EC, and salinity of water samples from all wells were significantly higher than the permissible limits. The anions were found to be below the WHO's acceptable standards for drinking water quality; whereas, the cations exceeded the WHO's allowable limits. Six water wells were contaminated with fecal coliform bacteria, suggesting that the water was unsafe for human consumption.

INTRODUCTION

Saudi Arabia's (SA) water scarcity is caused by extreme droughts due to reduced precipitation and its uneven spatial and temporal distributions, increased economic development demands, climate change impacts, rapid population expansion, and hosting refugees from neighboring nations (**WHO, 2008**). Groundwater is considered cleaner than surface water due to the protective benefits of soil and subsoil layers, such as longer residence durations, physical, chemical, and microbiological attenuation, etc.. (**El-Sheekh *et al*., 2010; Mutoti, *et al*., 2023**). In SA, drinkable water comes from desalinated seawater, treated wastewater, surface water and groundwater. SA uses 80% of its water from groundwater, which has an estimated reserve of 2259 billion m^3 (**Aly, *et***

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***al*., 2013**). KSA groundwater is drinkable. However, several areas have bacterial contamination due to defective pipelines or obsolete, poorly maintained storage facilities (**Alqahtani, *et al*. 2015**).

The study region's groundwater quality issues are mostly affected by climate and geology. Groundwater quality is affected by water-soil-sediment interactions, water flow, rock composition and predominating geochemical conditions (dissolution, redox state, precipitation, leaching, ion exchange, etc.) (**Singh, *et al*., 2011**). Despite the belief that groundwater is safer, in terms of contamination, than surface water due to the underground environment's natural filtering capacity; yet, primary environmental stresses affect groundwater quality (**Griebler, *et al*., 2010**). Over-abstraction and microbiological and chemical contamination threaten groundwater quality, which is used for numerous human activities and supplies drinking water (**Pedley & Howard 2015**).

In-situ assessment for pH, temperature, conductivity, turbidity, TDS, TSS, TS, DO, and arsenic were done on many Rabigh wells. This initiative should assist creating a long-term monitoring network, management program, and planning for sustainable groundwater management in Rabigh, Makkah, Saudi Arabia. In addition to nitrate (NO^{3-}), geogenic and anthropogenic physicochemical components including fluoride (F^-) and arsenic (As^-) regulate groundwater quality. Fluoride is essential to humans and animals, making its water supply behavior crucial. Higher quantities (1.5 mg L^{-1}) can cause dental and skeletal fluorosis in dry and semi-arid countries with little water (**Reddy, *et al*., 2010**). Groundwater has more fluoride than surface water; which may be a result of erosion from rocket (**Plant, *et al*., 2001**). Fluoride (F^-) is important for bone formation at sufficient quantities but harmful in excess (**Rao, *et al*., 2021; Subba, *et al*. 2022**). Several studies have found that lowering NO^{3-} levels in water is a priority to protect human health (**Ceballos, *et al*. 2021; Guo, *et al*. 2022**). In their 20-year groundwater NO^{3-} pollution investigation, **Bijay and Craswell (2021)** reported that agriculture and household trash cause groundwater NO^{3-} pollution. They found that NO3- concentrations were below national and international water quality standards, which do not adequately protect human health from contaminated drinking water.

Heavy metals (HMs) contamination, over-exploitation, and deterioration necessitate ongoing groundwater monitoring and evaluation. Toxicity, persistence, and bioaccumulation make HMs one of the most common environmental toxins (**Rezaei, *et al*., 2019**). Groundwater contains colloidal, particulate, and dissolved HMs from weathering rocks and volcanism-ejected products. Solid waste disposal, residential, and industrial effluents cause them. This study evaluated groundwater quality in some wells in Al-Khoarah, Rabigh Governorate. It investigated the physiochemical, heavy metal, and bacteriological characteristics of groundwater to identify contamination levels and sources. In result, we sought a reasonable solution.

MATERIALS AND METHODS

Area of study

Rabigh is a city in the Tihama Plain on the eastern coast of the Red Sea around 150 kilometers north of Jeddah. Rabigh has a severe problem with air pollution due to its proximity to several major industrial sites, notably Petro Rabigh and a cement mill. The study was conducted in Saudi Arabia's Al-Khorah, Rabigh Governorate, which is part of Makkah Province (Fig. 1). The study area is located at 22°48′N & 39°02′E. Rabigh is a historic town, with a population density estimated by more than 180,352 people (**Nayebare, *et al*., 2016**). The climate of Rabigh is characterized by high relative humidity with short rains and sudden periods; temperatures range between 32 and 39°C.

Sample collection

Water from ten wells in the Al-Khoarah, Rabigh area was sampled and collected in a 5-liter polyethylene bottles washed with distilled water. Bottles must be sterile in order to examine water samples bacteriologically. The bottles were prepared for collection by filling them with water and then rinsing them numerous times. The water sample was split in half at each sampling location; one half was used for field analysis.

Physio-chemical parameters

The physical and chemical properties of the water, such as turbidity, water temperature (ºC), pH, salinity (‰), dissolved oxygen (mg L^{-1}), electrical conductivity (EC) and total dissolved solids (TDS) were immediately measured in situ according to the procedures reported in standard methods (APHA, 2011).

Part two of the water sample was stored in a germ-free environment. The models were then carefully stored in ice boxes until they could be transported to the laboratory in the Faculty of Science at King Abdulaziz University, where they underwent additional analyses of the most critical chemical ions that determine water quality, including significant cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}) and major anions (F^{-1}, NO_3^{-1}, $SO_4^{-2,}$ and Cl^{-1}) according to the techniques reported in standard methods **(APHA, 2011)**.

Heavy and toxic metals

Heavy metal concentrations in well water were determined using a volume of 50ml of water that Whatman 42 filtered to remove most of the naturally occurring contaminants (Cu, Zn, Al, Cd, Cr, Pb, Hg, Ag, As, Ba, Be, Se and Sb). A water sample of 100 ml was placed in a Teflon beaker, and 5ml of nitric acid was added. The volume of this combination was reduced to 25ml by evaporation when it was digested on a hot plate. After being filtered again, they were placed in a clean polyethylene bottle for measurements container and measured using a 100ml volumetric flask. Inductively Coupled Plasma Emission Spectroscopy (ICPE-9000 - Shimadzu) was used to determine the concentrations of Ag, Al, As, Ba, Be, Cd, and Cr. In contrast, the IC-Dionex ICS-

5000 was used to determine the concentrations of Cu, Hg, Pb, Se, Sb, and Zn. Three replicates were analyzed for each metal's (Cu, Zn, Al, Cd, Cr, Pb, Hg, Ag, As, Ba, Be, Se, and Sb) concentration to record the mean value and standard deviation (S.D.) **(APHA, 2011)**.

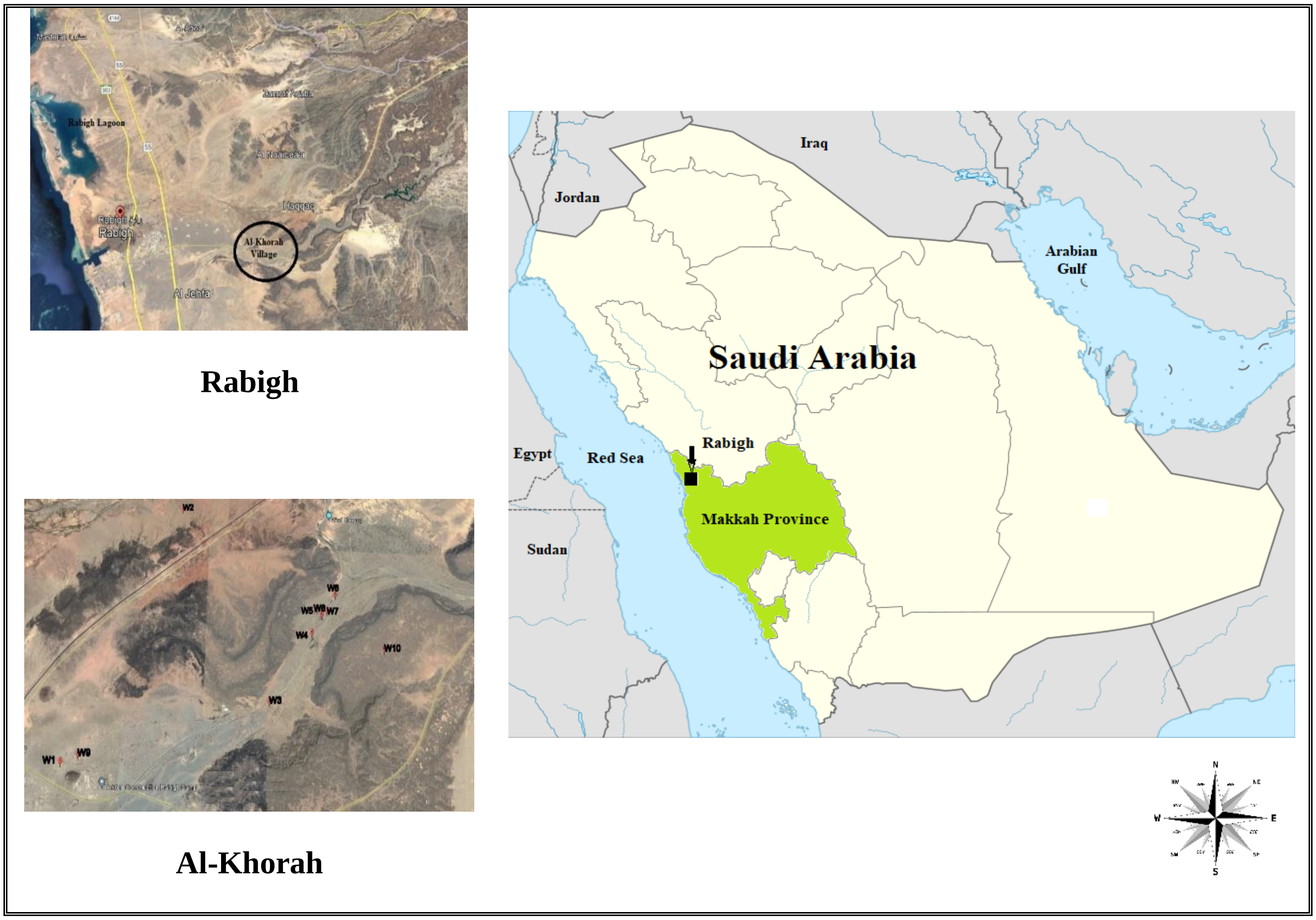

Fig. 1. A map of Rabigh Governorate showing the sampling sites **[Alharbi, 2020]**

Microbiological methods

The microbiological tests, including total coliform bacteria (TCB) and fecal coliform bacteria (FCB) were done according to the procedures mentioned in standard methods (WHO, 2008; APHA, 2011).

Statistical analysis

Statistical methods (correlation coefficient and multivariate analysis Canonical Analysis CCA) were performed to compare the bacteriological and physicochemical parameters in the wells by using Statistica Program Ver. 8 (**StatSoft, 2007**).

RESULTS AND DISCUSSION

Water quality affects natural watersheds and rural settlements. Saudi Arabia has the financial and economic resources to address its water dilemma. Still, other countries in worse situations do not and should not be forced to adjust to climate change and water scarcity. If mismanaged, virtual water trade could strain global water supplies. International water trade should combine global water-use efficiency and the distribution of scarcity. The water temperature of the studied wells was between 32 and 39°C. More evaporation occurs when temperatures are high. Rising water temperatures may foster illness conditions favorable to some (but not all) water-borne pathogens **(DeNicola, *et al*., 2015)**.

The average concentration of TDS in the selected groundwater wells were 4.052 ± 0.274 g L^{-1}. TDS ranged from the highest in W3 (5.780 ± 0.342 g L^{-1}) to the lowest in W7 (2.333 ± 0.072 g L^{-1}). Results reported by may authors (Al-Hasawi & Hussein, 2012; Abdel-Satar et al., 2017) are generally consistent with the current findings. Water with a TDS greater than 0.5 g L^{-1} is not suitable for human consumption as reported in World Health Organization guidelines, but it can be used to irrigate salt-tolerant plants such as palm trees. TDS was positively correlated with total coliform bacteria (TCB) and fecal coliform bacteria (FCB) (r = 0.50 & 0.57, respectively). This finding goes against the results of Aram et al. (2021). The previous authors found an inverse correlation between TDS and TCB but none between TDS and FCB in the groundwater, taken from the Tarkwa mining area in the western region of Ghana. The results are more or less similar to those of Alsuhaimi et al. (2016). Through investigating the groundwater in the Oqdus Area, Saudi Arabia. Sabino, Ireffey with his colleague guessed the fluctuation of TDS due to natural and anthropogenic influences (Sabino et al., 2022; Irfeey et al., 2023). The correlation coefficient between TDS and other parameters is presented in Tables (1, 2).

Wells (W8 and W3) had salinity readings of 1.267 ± 0.058 ppt and 3.167 ± 0.839 ppt, respectively, with an average of 2.347 ± 0.426 ppt throughout the wells (Fig. 2). The recommended maximum salinity of surface freshwater for drinking and irrigation is 0.5 ppt, the salt levels found in all the investigated well water samples are deemed to be highly excessive. The water from these wells is, therefore, unsafe to consume. These elevated levels may have resulted from the intrusion of water from the Red Sea into the groundwater **(Selvakumar *et al*., 2022; Subba *et al.*, 2022)**. The afore- entoned authors attributed the high salinity values to the stony composition of the well layers as reflected by marine evaporate deposits. There was a strong association between several physicochemical properties of groundwater and their increasing values, as shown in Tables (1, 2). TDS and salinity are positively related to transparency (r = 0.61).

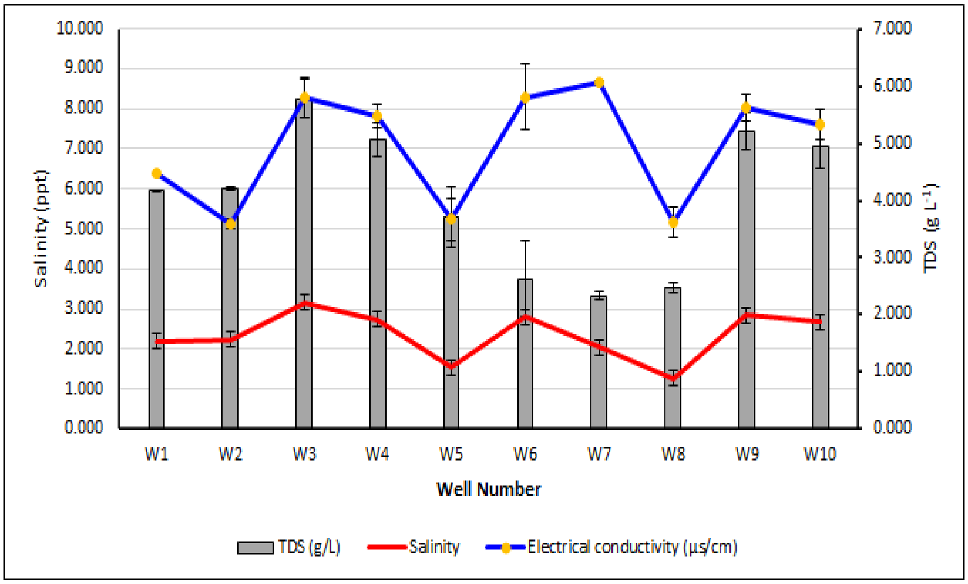

Fig. 2. Fluctuation of TDS, salinity, and electrical conductivity at the selected wells

Water's ability to carry an electrical current is quantified by its electrical conductivity (EC). Ions in water increase conductivity because they facilitate the transport of electric current through the solution. The mean electrical conductivity value in the well water samples was 4713 ± 103.46 µs/Cm. EC fluctuated between 2883 ± 101.32 µs/Cm at well 2 and 6623 ± 100.66 µs/Cm at well 7 (Fig. 2). All the well water samples had EC concentrations that were significantly higher than the maximum level allowed by WHO guidelines (750 µs/cm) **(WHO, 2008; Wehr & Sheath, 2015)**. Since electrical conductivity can be used as a proxy for the total amount of salts dissolved in water, this rise indicates an increase in the well water's dissolved salts and compounds.

pH readings from various wells at an alkaline site were over pH 7. W7 and W4 had pH readings of 6.747 ± 0.081 and 7.390 ± 0.280, respectively, while the average was 7.030 ± 0.109. All the pH values for the samples fell within the safe ranges recommended by the SASO, the USEPA and the WHO **(WHO 2008; Alsuhaimi, *et al*., 2016)**.

Water samples from the wells were analyzed for their levels of dissolved oxygen, which ranged from 7.640 ± 0.48 to 8.633 ± 0.04 mg L^{-1} (Wells 10 and 7, respectively), with an average of 8.341 ± 0.088 mg L^{-1}(Fig. 3). All the well water samples recorded an average DO concentration within the acceptable range established by the World Health Organization. The high levels of dissolved oxygen in water samples indicate its superior quality. Although dissolved oxygen has little effect on health, many individuals find the taste of water with very little oxygen unpleasant **(Joselyne, *et al*., 2022)**.

Table 1. Correlation coefficient between different physicochemical parameters in the studied wells

	pH	TDS	DO	S‰	EC	Cl^{-1}	SO_4	$NO\text{-}_3$	F	Mg	Ca	K	Na
pH	1.00												
TDS	0.51	1.00											
DO	-0.70	-0.44	1.00										
S‰	0.25	0.61	-0.14	1.00									
EC	-0.17	0.26	0.21	0.59	1.00								
Cr	0.61	0.97	-0.47	0.61	0.22								
Cd	0.63	0.96	-0.53	0.59	0.18								
Ba	0.44	0.91	-0.37	0.62	0.29								
As	-0.21	-0.50	-0.33	-0.29	0.00								
Al	0.55	0.98	-0.41	0.63	0.27								
Ag	0.54	0.75	-0.79	0.48	0.12								
Zn	-0.21	-0.30	0.39	0.35	0.20								
Pb	0.58	0.97	-0.46	0.59	0.25								
Cu	0.57	0.95	-0.45	0.57	0.14								
Cl^{-1}	0.57	0.97	-0.39	0.61	0.21	1.00							
SO4	0.37	0.08	-0.62	-0.15	-0.40	0.12	1.00						
NO-3	0.35	0.92	-0.28	0.58	0.25	0.90	-0.05	1.00					
F	0.60	0.67	-0.37	0.50	0.30	0.67	-0.02	0.69	1.00				
Mg	0.43	0.96	-0.21	0.64	0.32	0.97	-0.11	0.93	0.67	1.00			
Ca	0.42	0.94	-0.30	0.64	0.35	0.91	-0.13	0.90	0.67	0.96	1.00		
K	0.49	0.97	-0.34	0.62	0.27	0.98	0.04	0.97	0.71	0.97	0.91	1.00	
Na	0.47	0.76	-0.43	0.42	0.09	0.78	0.27	0.85	0.67	0.71	0.62	0.84	1.00

Table 2. Correlation coefficient between different heavy metals in wells under study

	Cr	Cd	Ba	As	Al	Ag	Zn	Pb	Cu
pH									
TDS									
DO									
S‰									
EC									
Cr	1.00								
Cd	1.00	1.00							
Ba	0.90	0.89	1.00						
As	-0.53	-0.47	-0.47	1.00					
Al	0.99	0.98	0.94	-0.54	1.00				
Ag	0.80	0.83	0.72	0.01	0.76	1.00			
Zn	-0.30	-0.30	-0.17	0.11	-0.24	-0.38	1.00		
Pb	1.00	0.99	0.91	-0.52	0.99	0.79	-0.31	1.00	
Cu	0.98	0.99	0.85	-0.51	0.96	0.78	-0.26	0.97	1.00
Cl^{-1}	0.99	0.98	0.90	-0.59	0.99	0.72	-0.23	0.99	0.98
SO4	0.17	0.25	0.15	0.44	0.14	0.54	-0.09	0.16	0.24
NO-3	0.91	0.90	0.77	-0.60	0.89	0.70	-0.39	0.91	0.91
F	0.71	0.69	0.54	-0.38	0.67	0.54	-0.33	0.68	0.67
Mg	0.95	0.92	0.89	-0.70	0.96	0.60	-0.23	0.95	0.92

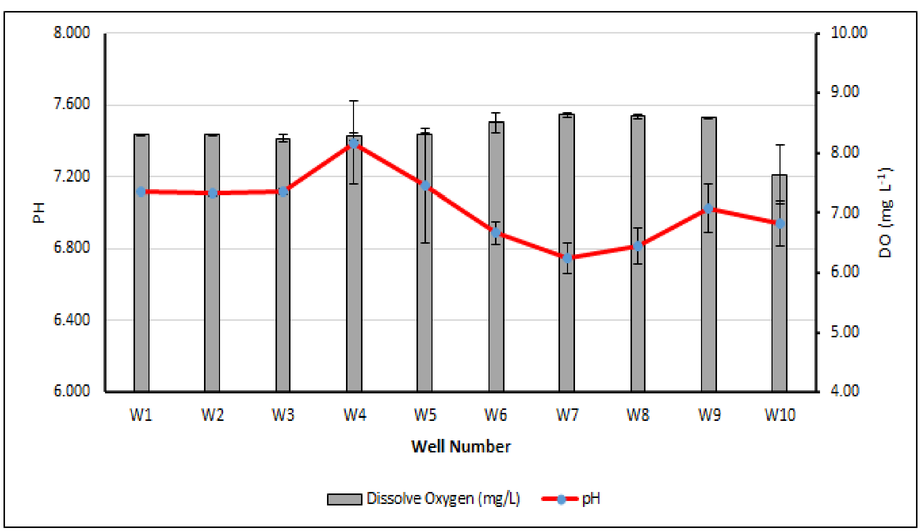

Fig. 3: Fluctuation of pH and dissolved oxygen (DO) in the selected wells

Cations

Hardness (calcium & magnesium)

Hard water does not lather well with soap, necessitating a higher consumption of soap. Total hardness is a water quality indicator used to characterize the impact of dissolved minerals like calcium and magnesium and to judge the water's fitness for consumption and other uses at home and in industry. W6 and W9 had magnesium readings of 57.159 ± 1.510 mg L^{-1} and 187.577 ± 10.806 mg L^{-1}, respectively, with an average of 116.993 ± 11.621 mg L^{-1}. Calcium levels ranged from 146.657 ± 1.510 mg L^{-1} in W7 to 375.553 ± 10.806 mg L^{-1} in W3, with a mean value of 246.464 ± 9.756 mg L^{-1} (Fig. 4). The total hardness readings of the well water samples were all within an acceptable range (400–500 mg L^{-1}) according to SASO **(Al-Redhaiman & Abdel Magid, 2002; Alsuhaimi, *et al*., 2016)**. According to **Al-Redhaiman & Abdel Magid (2002)**, the water in the analyzed well samples are classified as mildly hard water. This confirms the conclusion of **Al-Hasawi *et al*. (2018)**, which is consistent with the current findings. Table (1) shows the relationships between harndess and other physicochemical and bacterial variables. High Ca concentrations may be caused by the incorporation of calcic plagioclase feldspar into the alluvium from the basic igneous rocks in the area. The breakdown of ferromagnesian silicate minerals in the aquifer matrix also contributes to the high Mg content. High rates of evaporation precipitate carbonate minerals in the soil zone, and these minerals are then leached by the agricultural return flow, providing a source of Ca and Mg.

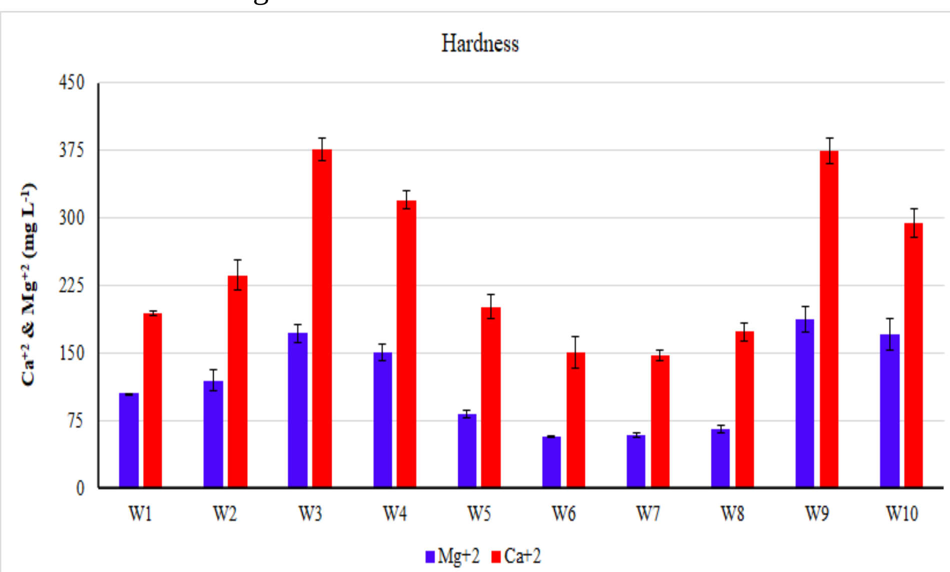

Fig. 4. Fluctuation of calcium and magnesium in the investigated wells

Sodium and potassium (Na^+ & K^+)

Cations make up around 93% of the total cations and anions in the groundwater in Al-Khoarah, thus lowering the quality and making it undrinkable. Na^+ and K^+ have good solubility and mobility and do not precipitate at any pH **(Siddiqui *et al*., 2005**). Na^+

concentrations in the well water samples were the lowest (351.512 ± 6.165 mg L^{-1}) in well 6 and the highest (879.730 ± 13.387 mg L^{-1}) in well 1, with an average of 574.005 ± 6.165 mg L^{-1} across all wells (Fig. 5). Human activity, such as sewage disposal may be to blame for the varying Na^+ concentrations between different wells. K^+ concentrations varied from 18.682 ± 0.165 mg L^{-1} in well 6 to 37.358 ± 1.387 mg L^{-1} in well 9. Wells 3 and 9 likewise showed high K^+ values, but wells 5, 6, 7, and 8 showed far lower concentrations. In every sample from a well, these levels were higher than the allowable maximum of 12 mg L^{-1}. Most terrestrial rocks include some amount of potassium, and because of the relative solubility of these minerals, the groundwater in these areas tends to have a higher concentration of potassium. Anthropogenic sources, including agricultural and industrial wastes, also increase K^+ concentrations in groundwater by seepage from the surface. Tables (1, 2) show that K^+ is chemically correlated to many other cations and anions, suggesting that they originate from the same place **(Mutoti *et al*., 2023; Zhang *et al*., 2023)**.

Anions

Nitrate (NO_3^{-1}) and sulphate (SO_4^{-2})

Anthropogenic activities involving nitrogenous compounds, such as mineral fertilizer and by-products of organic compounds from agriculture, septic systems, poultry, hog, or cattle manure, often enrich nitrate (NO_3) levels in aquatic environments to high levels **(Karlović, *et al*., 2022; Balacco, *et al*., 2023)**. In many marine environments, nitrate (NO_3) is naturally found in moderate concentrations. Nitrate concentrations ranged from 1.220 ± 0.139 to 5.060 ± 0.598 mg L^{-1} in W6 and W6, respectively, with 3.029 ± 0.380 mg L^{-1} being the average. On the other hand, the average sulphate concentration in the investigated wells was 63.904 ± 4.402 mg L^{-1}, ranging from 34.258 ± 4.995 mg L^{-1} at W9 to 90.222 ± 0.01 mg L^{-1} in W1 (Fig. 6). The quantities of nitrate and sulfate in the examined samples were within the advised limits of 45 mg L^{-} and 250 mg L^{-1} standards, respectively, established by WHO and SASO **(WHO, 2008 & Alsuhaimi, *et al*., 2016)**. There is no discernible pattern in the levels of sulphate and nitrate. The present study findings corroborated with **Widory *et al.* (2004)** conclusions. The high sulfate content of well water is typically caused by magnesium sulfate or sodium sulfate in the surrounding natural sediments. Nitrate and sulphate concentrations too high to drink change the water taste and make it unpleasant **(Davis, 2010)**.

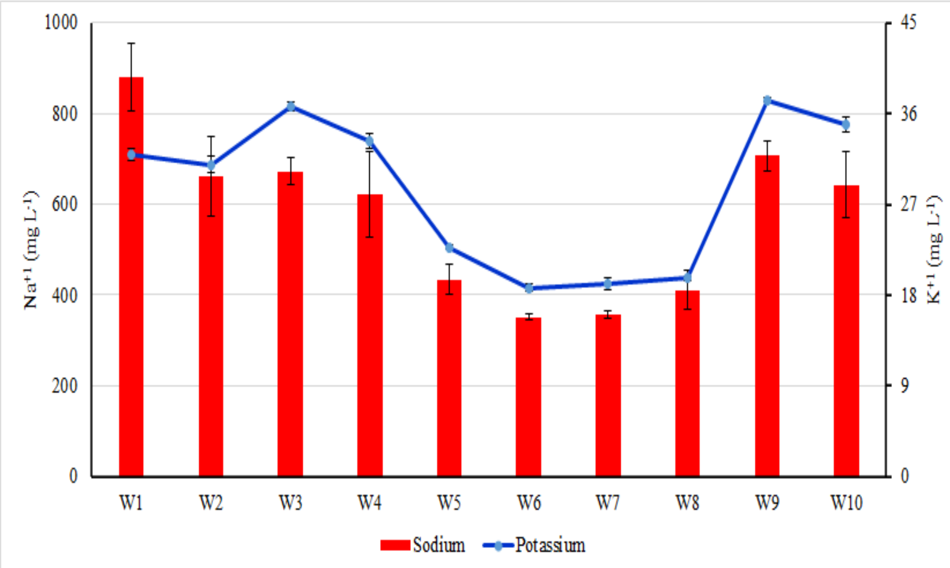

Fig. 5. Fluctuation of sodium and potassium in the investigated wells

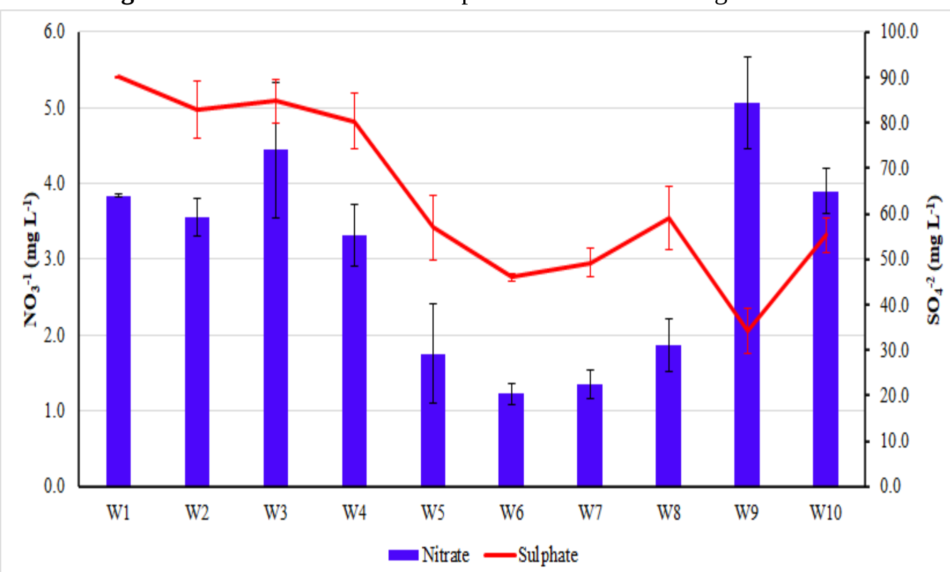

Fig. 6. Fluctuation of nitrate and sulphate in the investigated wells

Chlorine (Cl^{-}) and fluoride (F^{-})

One of the most influential characteristics of water quality that directly impacts human health is chlorine (Cl^{-}) (**Pius *et al.*, 2011**). Well water samples averaged 0.789 0.105 mg L^{-1} of free chlorine. From W6 (0.540 ± 0.026) to W3 (1.020 ± 0.122), mg L^{-1} of chlorine was measured. Well 3, 4, 9 & 10 recorded the highest values among the studied wells (Fig. 7). Chlorine levels in Saudi Arabia must be between 0.2 and 5.0 mg L^{-1}. The measured chlorine concentration was quite like that found in Saudi Specifications **(Al-Hasawi *et al.*, 2018)**. Fluoride (F^{-}) is an important micronutrient that can harm health if deficient or overexposed. It covers 0.06– 0.09% of the earth's crust and enters the body through drinking water. Fluoride below 1.5 mg L^{-1} may enhance bone growth and prevent dental cavities. Whereas, fluoride above 1.5 mg L^{-1} can induce skeletal and dental fluorosis. WHO allows 1.5 mg L^{-1} fluoride in drinking water. Fluoride occurs naturally in soil and groundwater, but fluorinated industrial waste, pesticides, and phosphate fertilizers used in agriculture can boost fluoride concentrations **(Subba *et al*., 2022)**.

Heavy metals

Several heavy metals are harmful to humans despite being important to manufacturing. Recent studies **(Amiri *et al*., 2021; Zhao, *et al*., 2021)** have examined how much heavy metals have contaminated groundwater and surface water. Meanwhile, human activity is increasingly the leading cause of groundwater pollution. Throughout this study, we could put a number on 13 different trace metals. Be, Sb, Se, and Hg had detection limits below the capabilities of the instruments employed to analyze them. Table (3) shows the variation in heavy metals among the investigated wells.

Copper (Cu) is an essential element for human survival and flourishing. W7 and W3 both measured values between 0.256 and 0.387 mg L^{-1}. All the well water samples were found to have copper contents below the threshold of 1 mg L^{-1} established by the report of USAO **(USGAO, 2020)**. Although copper is necessary for human and animal survival, it causes serious health hazards when present in excessive quantities in the environment.

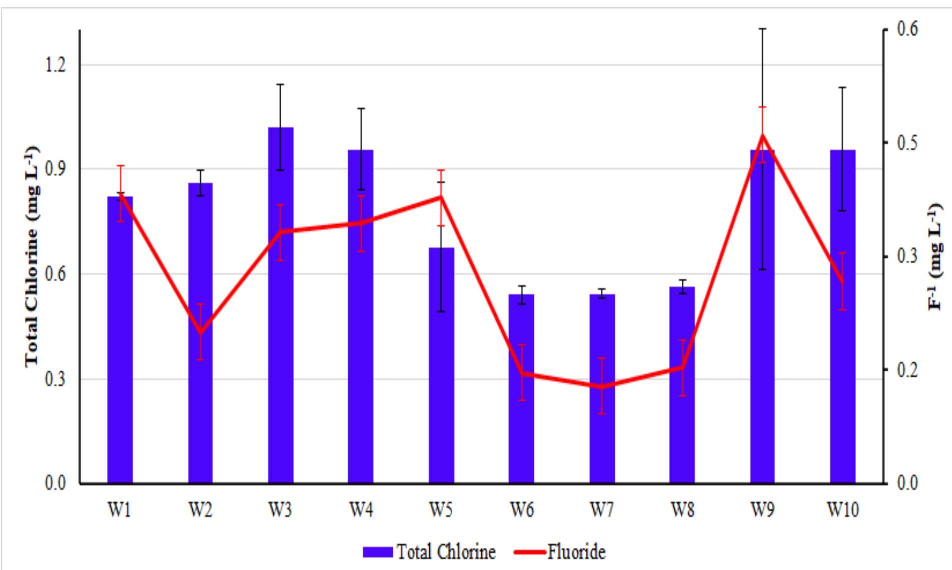

Fig. 7. Fluctuation of chloride and fluoride in the investigated wells

For W6 and W3, lead values were between 0.137 and 0.266 mg L^{-1}. All the well water samples had Pb contents above the maximum contaminant levels established by the SASO, the WHO, and the GCCS, which are all 0.01. Lead is discharged into groundwater primarily from natural and human causes. Thus, well water in the examined area may be marginally contaminated. Lead toxicity increases with exposure to even trace amounts **(Sankhla, 2019)**. Lead poisoning is a serious health risk that can result in death or irreversible damage to the kidneys, central nervous system and brain (**USGAO, 2020**). Pb's positive connection with Cr, Cd, Al, Ba, and Ag and its negative correlation with As suggest that these metals may have shared a common antecedent **(Bantan *et al*., 2020)**.

Table 3. Fluctuation of heavy metals in the investigated wells (mg L^{-1})

	Cu	Pb	Zn	Cr	Cd	Al	Ag	As	Ba
W1	0.362	0.211	0.023	0.064	0.015	0.049	0.010	0.060	0.099
W2	0.356	0.222	0.031	0.067	0.016	0.052	0.010	0.049	0.107
W3	0.387	0.266	0.037	0.077	0.019	0.066	0.014	0.052	0.176
W4	0.366	0.244	0.110	0.072	0.018	0.060	0.009	0.049	0.150
W5	0.292	0.171	0.021	0.052	0.010	0.041	0.002	0.059	0.090
W6	0.258	0.137	0.236	0.044	0.007	0.033	0.000	0.062	0.072
W7	0.256	0.141	0.127	0.044	0.007	0.033	0.000	0.059	0.075
W8	0.262	0.143	0.018	0.045	0.007	0.033	0.000	0.049	0.078
W9	0.364	0.237	0.016	0.071	0.016	0.055	0.004	0.027	0.133
W10	0.368	0.230	0.174	0.068	0.016	0.057	0.002	0.033	0.137
Permeable concentration (Safe limit concentration) *									
Range	1.00	0.01	1.00	0.05	0.003	1.00	0.05	0.01	1.30

* According to **Al-Zahrani *et al.* (2017)** and **Badr and al Naeem (2021)**.

In W9 and W6, zinc concentrations varied between 0.016 and 0.236 mg L^{-1}. Zn concentrations in well 6 were the highest, while wells 1, 5, 7, and 8 showed the lowest values. The zinc levels in all well water samples were below the regulatory threshold of 1 mg L^{-1} of **USGAO (2020)**. Zinc is a mineral with vital biological and physiological implications for humans, particularly in normal growth and development. Nevertheless, excessive zinc consumption may have harmful effects on human health **(Bhowmik *et al*., 2010)**.

For W6-7 and W3, the chromium (Cr) levels were 0.044 and 0.077 mg L^{-1}, respectively. Wells 6, 7, and 8 had the lowest Cr amounts among those studied. According to **Badr and al Naeem (2021)**, the maximum chromium concentration in drinking water is 0.05 mg L^{-1}. At the same time, all the well water samples tested somewhat higher. Toxic chromium pollution is linked to cancer in humans. Many natural processes, such as the deterioration of chromite-containing rocks and human-caused processes, such as sewage seepage and industrial waste, contribute to its introduction into groundwater **(Miao *et al*., 2021)**.

The cadmium values in W6 and W3 were between 0.007 and 0.019 mg L^{-1}. Wells 1, 2, 3, 4, and 9 had the greatest Cd amounts, whereas wells 6, 7, and 8 had the lowest. All the well water samples had cadmium contents slightly higher than the allowable limit of 0.003 mg L^{-1} **(Badr & al Naeem, 2021)**. In addition to human activities like sewage, industrial, and agricultural runoff, cadmium can enter groundwater from natural processes such as weathering cadmium-bearing mineral ores **(Houng & Lee, 1998)**. All the other heavy metals (copper, lead, aluminum and Ba) are positively connected with cadmium. The negative correlation with arsenic (r = -0.47) suggests they all come from the same place. Given that fertilizers used in agriculture are a source of Cd and Cu in groundwater (**Vetrimurugan, *et al*., 2017**), their close relationship (r = 0.99) suggests that they share a common origin from agricultural operations.

With respect to W6 and W3, the Al values were between 0.033 and 0.066 mg L^{-1}. Except for wells 3, 4, 5 and 8, all the wells registered high levels of Al. According to **Badr and al Naeem (2021)**, all well water samples tested had Al concentrations below the maximum allowable level of 1mg L^{-1}. Due to its abundance in the earth's crust, aluminum is the primary contributor to aluminum levels in groundwater.

On the other hand, concentrations of silver varied between W6 (Zero, within the detection limit) and W3 (0.014 mg L^{-1}). Well 3 had the greatest Al concentration. Whereas, wells 5, 6, 7 and 8 recorded silver values just below detection. The levels of Ag in all the well water samples fall within the WHO-recommended range for acceptable levels of Ag in water **(Al-Zahrani *et al*., 2017; Badr & al Naeem, 2021)**. Despite its low and unpolluted quantities in groundwater, silver is likely to have originated from the same place as other metals with which it shares a strong affinity, including copper (r = 0.78) and lead (r = 0.79) **(Vetrimurugan *et al*., 2017)**.

Arsenic occurs naturally in the earth's soil. Groundwater can be contaminated if it dissolves. Both W9 and W6 saw levels between 0.027 and 0.062 m mg L^{-1}. According to WHO and other references **(Badr & al Naeem, 2021)**, arsenic contents in all well water samples were slightly above the permitted level of 0.01 mg L^{-1}. Inorganic arsenic is highly hazardous **(Alansari, *et al*., 2021)**, and research suggests it may cause cancer if exposed to it over time **(Saw, *et al.*, 2022)**. Arsenic was found in shallow wells in a similar study conducted in the Bengal Delta **(Chakraborti, *et al.*, 2013)**.

Barium is a chemical element found in low concentrations in soil. For W6 and W3, it varied between 0.072 and 0.176 mg L^{-1}. All well water samples have barium contents below the safe limits of 0.7 and 1.3 mg L^{-1} in water established by the World Health Organization and others **(Badr & al Naeem, 2021)**.

In general, the majority of the heavy metals in the 10 wells studied in the Rabigh region were comparable to the results of the studies of **Al Ahmadi *et al*. (2019)** and **Alfaifi *et al*. (2021)**, which confirmed that the water in the investigated wells was safe to drink in terms of its heavy metal content, except for lead, which was slightly elevated in this study and can be considered a relatively hazardous substance.

Microbiological assessment

The microbiological quality of well water in the Rabigh area was assessed by the number of total coliform bacteria (TC, MPN/100 ml), fecal coliform bacteria (FC, MPN/100 ml), and total bacteria (TB, cfu/ml). Coliform bacteria are the most common organisms used as an indicator in water quality monitoring. The presence of these organisms in a high density is a strong indicator of either sewage or fecal contamination **(Alansari *et al*., 2021)**. The enumerations of the three types of total coliforms, fecal coliforms, and total bacteria of the ten wells are listed in Fig. (8).

Wells W5, W6, W7, and W10 had no detectable total coliform, while wells W2, W3, and W8 had a relatively low total coliform count (502 MPN/100 ml). Total coliform counts, on the other hand, peaked at their highest on days 4 and 9 (37966 and 44795 MPN/100 ml). These findings suggest that fecal coliform levels in some wells were greater than the optimum fecal coliform-free level set by international guidelines **(Ferrer *et al.* 2020; Azma & Zhang, 2021)**. It was stated that agricultural nitrate fertilizers and manures had contaminated groundwater. Nitrate is a nutrient that can be used by bacteria. It's also common for them to be bacterial and pesticide contaminated when there are significant amounts of nitrate (**Aydin, 2007; Vadde *et al*., 2018**). Agricultural chemical and organic waste land application, infiltration of irrigation water, septic tanks, and infiltration of effluent from sewage treatment plants, pits, lagoons, and ponds used for storage are all potential sources of microbiological and physico-chemical quality that adversely affected the quality of groundwater **(Aydin, 2007)**.

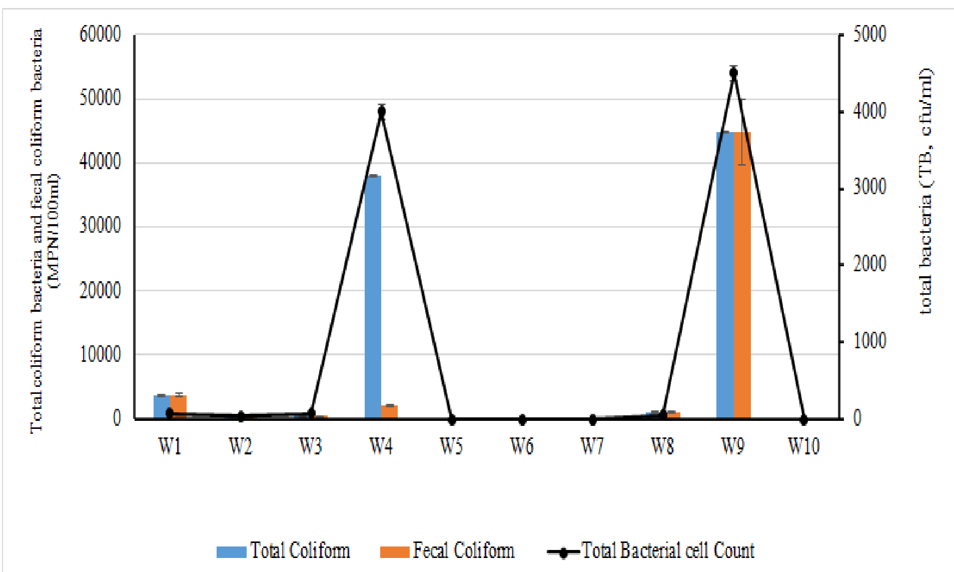

Fig. 8. The enumerations of the three types of total coliforms, fecal coliforms and total bacteria of investigated wells

Like total coliforms, fecal coliforms were undetectable at Wells No. 5, 6, and 7. W2 and W3 had the lowest fecal coliform counts (138 and 502 MPN/100ml), whereas W4 and W8 had moderate counts (2192 and 1085 MPN/100ml). The highest fecal coliform count was detected in the water samples of W9 (44795 MPN/100ml). Total coliform and fecal coliform bacteria in well water reflect the possible dangers to human health and suggest recent fecal contamination from human or animal excreta or may be of natural origin. Nonetheless, this water may be suitable for irrigation or other non-drinking applications around domestic uses **(Ferrer *et al*., 2020; Azma & Zhang, 2021)**. Microbiological testing revealed that some of the wells, including numbers 1, 4, 8, and 9, were severely tainted and could threaten public health.

The total number of bacterial cells was zero in W5, W6, W7 and W10. W4 and W9 were updated to reflect the maximum values of 4000 and 4500 cfu/ml. The number of TB organisms in well water samples 4 and 9 was higher than the maximum microbial load allowed by the US Environmental Protection Agency (USEPA) (500 CFU/mL) **(Azma & Zhang, 2021)**. Wells 4 and 9 contained detectable levels of TBC contamination, which could have resulted, either from a lack of adequate cleaning and periodic maintenance of the groundwater well or from mixing with water already contaminated by sewage intrusion.

Species assemblages and their environments can be better understood using canonical correspondence analysis (CCA), a multivariate technique (Fig. 9). Total coliform counts were positively correlated with several physicochemical factors, including nitrate and calcium levels. Several studies confirm a negative correlation between sulfate and magnesium, potassium and sodium **(Maghraby & Bamousa, 2021; Kenniche *et al*., 2022)**.

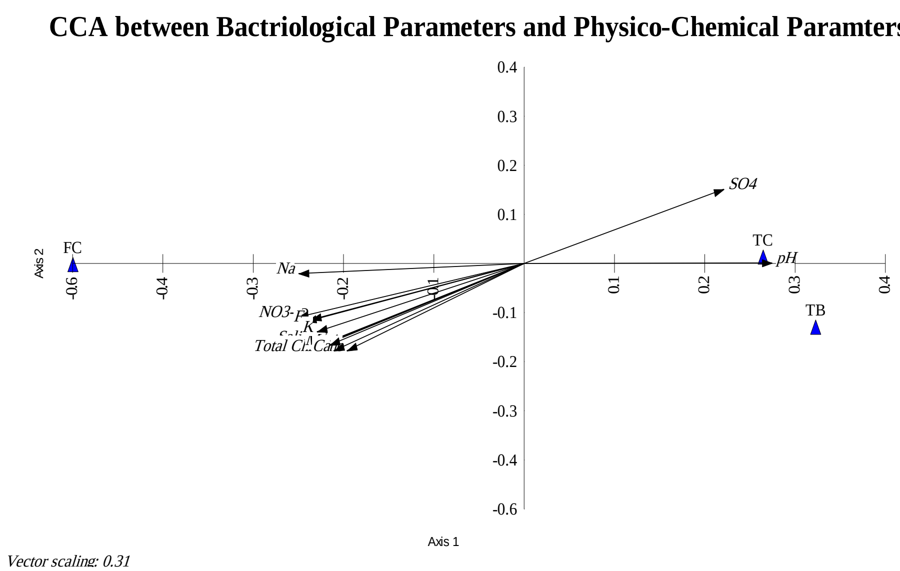

Fig. 9. Canonical correspondence analysis (CCA) between bacteriology and physicochemical parameters

CONCLUSION

Pollutants in surface water and those originated from human activities enter the groundwater system. Although these contaminants enter groundwater slowly, their numbers steadily grow as they are continually expelled. Many factors including human waste contribute to the tainting of groundwater reservoirs. Sewage systems and landfills located near groundwater reservoirs and wells are a major source of contamination and microorganisms in the water. Chemical fertilizers and pesticides used on farmland often end up in neighboring aquifers after being filtered by water. Hazardous chemicals, petroleum byproducts, and detergents are just some of the examples of industrial waste that can be created when proper disposal procedures are not followed. The well water is crucial to our daily lives since it provides potable water, as well as water for other domestic and agricultural uses. If there are any issues, you'll have more time to fix them if your well is in good shape. That's a money- and time-saver.

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