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Chemical Evaluation of Well Water for Agriculture in Fallujah City

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ABSTRACT

Background: Water is an indispensable natural resource for human beings, plants and agriculture. Towns in Anbar In the city of Fallujah, Anbar province and the local people are very dependent on underground water from wells for drinking and irrigation.

Methods: Water from five wells was assessed for physicochemical parameters such as EC, pH, TDS, turbidity, dissolved oxygen (DO), hardness, soil fractions (sodium adsorption ratio [SAR]), major ions and heavy metals.

Result: All the parameters were within World Health Organization (WHO) limits although difference exist among the wells based on soil formation feature. The findings confirm that water from the five wells is suitable for both consumption and irrigation, with no adverse effects on soil structure or crop productivity.

Key words: Agricultural suitability, Chemical study, Heavy metals, Well water.

INTRODUCTION

Globally, groundwater accounts for nearly 97% of the Earth's available freshwater and is stored beneath the surface in geological formations (Albbanqeeyah *et al*., 2024; Ramos *et al*., 2021). With rapid population growth, urban expansion and socioeconomic development, groundwater particularly well water has become a vital resource for domestic consumption and agricultural irrigation, especially in arid and semi-arid regions (Beyene *et al*., 2019; Guo *et al*., 2021). Agricultural irrigation is considered one of the most sensitive components of water resource management systems due to its high demand and direct impact on food security (Vranešević *et al*., 2024; Sharma *et al*., 2016). Globally, agriculture consumes approximately 70% of total freshwater withdrawals, while nearly 20% of cultivated land depends on irrigation practices (Vranešević *et al*., 2024). In Iraq, particularly in areas surrounding Fallujah City within Anbar Governorate, groundwater extracted through wells constitutes a primary source for both drinking and irrigation purposes (Al-Kubaisi *et al*., 2025).

The conservation and sustainable management of groundwater resources are therefore essential, especially in regions where agricultural productivity and land sustainability are highly dependent on well water. Degradation of groundwater quality directly affects soil properties and crop productivity, leading to serious environmental and economic consequences (Maghrebi *et al*., 2021; Noori *et al*., 2021). It has been reported that the use of poor-quality irrigation water adversely affects nearly 20% of agricultural soils worldwide, accelerating processes such as salinization, alkalization and waterlogging (Payen *et al*., 2016). In arid regions such as Anbar Governorate, declining groundwater availability and quality further exacerbate water scarcity and limit agricultural development.

Groundwater and well water are often characterized by elevated concentrations of dissolved ions originating from the weathering and dissolution of geological materials, which increases salinity levels and poses risks to agricultural soils (Brhane, 2018). Numerous studies have demonstrated that the chemical composition of groundwater is governed by a combination of natural and anthropogenic factors, including lithology, soil-rock interactions, geochemical processes, climate, recharge conditions and topography, in addition to human activities such as agricultural practices, industrial discharge, land-use change and urban expansion (Albbanqeeyah *et al*., 2024; Vranešević *et al*., 2024; Gu *et al*., 2017; Rawat *et al*., 2019). These interacting processes often result in groundwater quality deterioration, rendering it unsuitable for various uses, particularly irrigation (Rao *et al*., 2021; Gugulothu *et al*., 2022). In regions lacking good-quality surface water, farmers are compelled to use sodic groundwater for irrigation, posing serious risks to soil health and the environment (Pradeepa *et al*., 2019).

Geochemical processes controlling groundwater quality are largely influenced by mineral dissolution, ion exchange, evaporation, flow paths and recharge mechanisms (Li *et al*., 2013; Saravanan *et al*., 2015; Subba Rao *et al*., 2017;

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Gugulothu *et al*., 2022). In arid and semi-arid regions, including Anbar Governorate in Iraq, intensive use of well water combined with anthropogenic pressures-such as excessive application of chemical fertilizers and pesticides, inadequate drainage systems, urban and industrial development and animal waste disposal-further degrades the physical and chemical characteristics of groundwater (Koffi *et al*., 2017; Wagh *et al*., 2019; Gugulothu *et al*., 2022). Such degradation not only affects soil productivity but also poses risks to human health and economic sustainability, ultimately constraining agricultural output.

Water quality is a critical determinant of its suitability for irrigation, as groundwater chemistry directly influences soil fertility, structure and permeability, thereby affecting crop yields (Guo *et al*., 2021). These effects arise mainly from soil-water interactions, particularly ion exchange processes (Bian *et al*., 2018; Dev and Bali, 2019; Guo *et al*., 2021). Elevated sodium concentrations in irrigation water are especially problematic, as they reduce soil hydraulic conductivity, decrease permeability and impair internal drainage, ultimately leading to soil degradation (Guo *et al*., 2021; Sahab *et al*., 2025). Consequently, evaluating the physicochemical properties of groundwater is essential before its use in irrigation. Previous studies have assessed irrigation water quality based on parameters such as electrical conductivity (EC), total dissolved solids (TDS), pH, total hardness (TH), salinity indicators, sodium adsorption ratio (SAR), residual sodium carbonate (RSC), turbidity, major cations and anions, nutrients and selected heavy metals (Guo *et al*., 2021).

In Fallujah City, located in Anbar Governorate, Iraq, local communities predominantly rely on well water for irrigating agricultural lands. However, the quality of this water has not been comprehensively evaluated and its suitability for irrigation remains uncertain (Sahab *et al*., 2025). The study area is exposed to several potential sources of groundwater contamination, including sewage leakage, uncontrolled solid waste disposal, excessive use of chemical fertilizers, animal waste and industrial effluents. Despite the importance of groundwater quality assessment in this region, there is a lack of systematic studies addressing the physicochemical characteristics of well water and its appropriateness for agricultural use.

Therefore, the present study aims to evaluate the suitability of well water for agricultural irrigation in selected areas of Fallujah City by analyzing key physicochemical parameters from five irrigation wells. The investigated parameters include EC, TDS, pH, turbidity, dissolved oxygen (DO), total hardness (TH), soil texture distribution, major cations (Ca^{2+}, Mg^{2+}, Na^{+}), major anions (Cl^{-}, SO_4^{2-}, HCO_3^{-}, NO_3^{-}, PO_4^{3-}), sodium adsorption ratio (SAR) and selected heavy metals (B, Cd and Pb). The findings of this study are expected to provide a scientific basis for groundwater management, support the implementation of appropriate treatment and mitigation strategies and contribute to sustainable agricultural development in the region.

MATERIALS AND METHODS

Study area

The study was conducted in Fallujah City, located in Anbar Governorate, western Iraq (33°35′N, 43°78′E) Fig 1. The study area covers approximately 40 km^2 and lies at an elevation of about 44 m above sea level. The region is characterized by a hot desert climate, with mean annual rainfall of approximately 150 mm and high evaporation rates. Five groundwater wells commonly used for agricultural irrigation were selected from different locations: Al-Halabsa, Al-Saqlawiya, Al-Naimiya, Al-Sajr and Al-Karma. The depths of the selected wells ranged between 9 and 20 m, representing the shallow groundwater system exploited for irrigation in the area.

Sample collection

Groundwater and soil samples were collected during February and April 2024 to represent two contrasting seasonal conditions: late winter (higher recharge potential) and early spring (increased agricultural activity). Prior to sampling, each well was purged continuously for

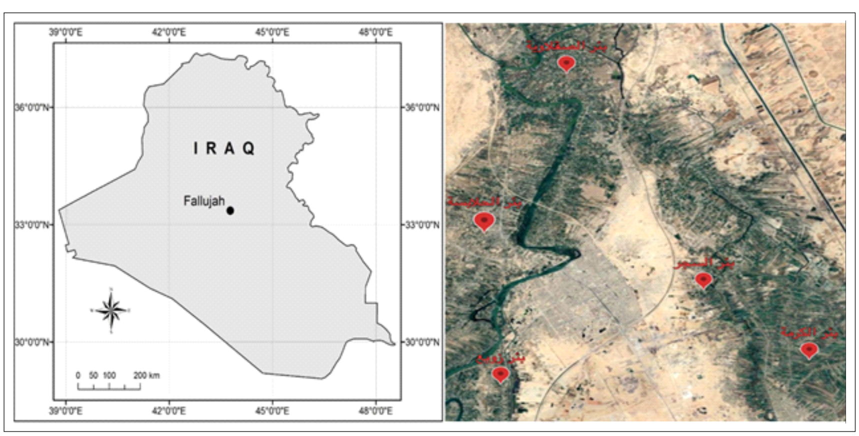

Fig 1: Illustrates the location of the study area in Fallujah, Anbar Governorate, along with the groundwater wells designated for sampling sites [Al-Sajr, Al-Karmah, Al-Naimiyah (Zubaa), Al-Halabsa and Al-Saqlawiyah (Al-Sabakhna)].

20 minutes to remove stagnant water and ensure sample homogeneity Fig 2. Water samples were collected in pre-cleaned and sterile polyethylene bottles (1 L capacity). Soil samples were collected from the irrigated zones adjacent to each well at a depth of 0-30 cm using clean tools.

Samples intended for microbiological (coliform) analysis were collected separately using sterile containers and appropriate adsorbent materials. All samples were immediately labeled as B1-B5 for groundwater samples and C1-C5 for soil samples, preserved at 4°C in insulated containers and transported to the laboratory on the same day for physicochemical analysis Table 1.

Fig 2: Shows how to take samples from wells using a water pump.

Physical analyses

Total hardness (TH) of groundwater samples was determined using the standard EDTA titrimetric method. Soil particle-size distribution (sand, silt and clay fractions) was determined using the hydrometer method after the removal of carbonates and organic matter, following standard soil analysis procedures Table 1.

Chemical analyses

Table 1 showed some of chemical parameters including Electrical conductivity (EC), pH, total dissolved solids (TDS), turbidity and dissolved oxygen (DO) were measured using calibrated digital meters according to standard methods. Major cations (Ca^{2+}, Mg^{2+}, Na^{+}) and anions (Cl^{-}, SO_4^{2-}, HCO_3^{-}, NO_3^{-}, PO_4^{3-}) were analyzed using a combination of titrimetric methods, flame photometry and spectrophotometry, following standard analytical protocols.

Soil chemical properties were determined using a soil-water extract prepared at a ratio of 1:5 (w/v), after thorough shaking and filtration. Sodium adsorption ratio (SAR) was calculated using the concentrations of Na^{+}, Ca^{2+} and Mg^{2+} according to Richards (1954). Heavy metals, including lead (Pb), cadmium (Cd), boron (B) and copper (Cu), were measured using atomic absorption spectrometry (AAS).

Quality control and data validation

Quality assurance procedures included instrument calibration using certified standard solutions prior to

Table 1: Standard permissible limits for physicochemical parameters for assessing well/groundwater quality (Ayers and Westcot, 1985; WHO, 2022).

Category	Parameter		Standard/permissible limit for (Irrigation)
Physical parameter	Total hardness (TH)		<500 mg/L
	Turbidity (Tur)		<5 NTU
Chemical parameter	Total dissolved solids (TDS)		≤1000 mg/L
	Dissolved oxygen (DO)		>5 mg/L
	Electrical conductivity (EC)		≤1500 µS/cm
	pH		6.5-8.5
	Sodium adsorption ratio (SAR)		<10 mg/L
		Cations	
	Calcium (Ca^{2+})		≤75 mg/L
	Magnesium (Mg^{2+})		≤150 mg/L
	Sodium (Na^{+})		≤200 mg/L
		Anions	
	Chloride (Cl^{-})		≤250 mg/L
	Sulfate (SO_4^{2-})		≤250 mg/L
	Carbonates (CO_3^{2-})		Alkalinity >200 mg/L
	Bicarbonate (HCO_3^{-}),		Undesirable <610 mg/L
	Nitrate (NO_3^{-})		≤50 mg/L
	Phosphate (PO_4^{3-})		5 mg/L
		Heavy metals	
	Boron (B)		0.7-3 mg/L
	Cadmium (Cd)		≤0.003 mg/L
	Lead (Pb)		≤0.01 mg/L

analysis, duplicate sample measurements and the use of reagent blanks. The ionic balance error between total cations and anions was maintained within ±5%, indicating acceptable analytical accuracy. The obtained results were evaluated and compared with the maximum allowable limits recommended by the World Health Organization (WHO) for irrigation water quality.

RESULTS AND DISCUSSION

The physicochemical characteristics of the analyzed groundwater samples (B1-B5) and soil extracts (C1-C5) are presented in Table 2-4. The pH of groundwater samples ranged from near-neutral to slightly alkaline values (6.9-7.8), with a noticeable alkaline tendency in samples B4 and C4. This behavior is primarily attributed to elevated bicarbonate concentrations, which exert a buffering effect on groundwater and soil systems, particularly in carbonate-rich geological environments. Similar pH ranges have been reported for groundwater in arid and semi-arid regions of Iraq and neighboring countries. All measured pH values fall within WHO guideline limits, indicating no immediate restriction for irrigation or domestic use. Soil extracts also exhibited weak alkalinity, commonly associated with carbonate dissolution and mineral weathering processes in calcareous soils.

Electrical conductivity (EC) and total dissolved solids (TDS) values reflected relatively low to moderate mineralization levels in the investigated groundwater. Although EC and TDS values varied spatially among wells, the overall salinity hazard can be classified as low to moderate, suggesting limited salt accumulation and minimal risk of soil salinization under current irrigation

Table 2: Some parameters of water and soil extract samples of five wells.

Samples	Ph	Ec (ms/cm)	Tds (mg/l)	Tur (NTU)	Do (mg/l)	Th (mg/l)
B1	7.26	1.9	950	0.6	6.82	370
B2	6.9	3.3	1650	0.9	6.34	650
B3	7.5	8.7	1350	1.2	6.47	530
B4	7.8	2.7	170	2.3	6.04	670
B5	7.22	3.4	4350	3.6	4.19	1730
C1	6.88	17.5	8750	290	1.5	3064
C2	7.49	3.1	1550	175	1.13	544
C3	7.61	4.1	2050	550	0.36	719
C4	7.8	4.3	2150	440	0.84	754
C5	7.5	3.6	1800	300	0.99	640

Table 3: Volumetric distribution of soil components by volume for five wells from various locations.

Samples	Location samples of wells	Soil texture	Sand (%)	Silt (%)	Clay (%)
B1	Al-Halabsa	Sandy clay loam	55.0	15.0	30.0
B2	Al-Saqlawiya	Loam	40.0	40.0	20.0
B3	Al-Naimiya	Silty loam	25.0	60.0	15.0
B4	Al-Sajr	Clay loam	30.0	30.0	40.0
B5	Al-Karma	Sandy clay loam	52.0	18.0	30.0

Table 4: Chemical characteristics of the samples of water and soil extract of five wells.

Samples	Unit (mg/L)											
	SAR	Ca^{2+}	Mg^{2+}	Na^{+}	$SO4^{-2}$	Cl^{-}	HCO_3^-	NO_3^-	PO_4^{3-}	B	Cd	Pb
B1	0.315	21	5.65	2.67	1.91	7.5	82.05	2	0.08	0.1	0.0002	0.002
B2	0.189	25.9	5.05	2.1	0.84	4.26	99.86	1.5	0.1	0.08	0.0003	0.001
B3	0.4	16.5	3	4.19	3.26	27.4	21.5	3.5	0.12	0.2	0.0005	0.003
B4	0.52	23.2	16.4	5.65	3.32	21.7	123.72	2.5	0.2	0.15	0.0004	0.004
B5	0.472	25.3	3	5.34	4.97	18.1	67.73	1	0.1	0.12	0.0003	0.002
C1	0.32	12.35	5	3.26	2.16	8.17	40.49	12	1.2	0.6	0.001	0.006
C2	0.599	25.95	1.1	6.22	3.28	17.4	57.62	8	0.8	0.4	0.0015	0.004
C3	0.27	26	8.15	2.7	1.61	7.1	95.28	15	1.6	0.8	0.0012	0.005
C4	0.313	26	6.22	3.52	3.06	12.07	83.43	10	1	0.55	0.0013	0.007
C5	0.414	15.6	4.18	4.33	1.81	14.91	44.83	6	0.7	0.35	0.0009	0.004

practices. This indicates that the groundwater is generally suitable for agricultural use; however, localized increases in salinity cannot be excluded under long-term irrigation without proper drainage management.

Dissolved oxygen (DO) concentrations in groundwater samples B1-B4 (6.04-6.82 mg/L) indicate well-aerated conditions and limited organic pollution, consistent with shallow aquifer recharge and active water renewal. In contrast, the lower DO value observed in B5 (4.19 mg/L) may reflect localized stagnation, reduce hydraulic connectivity, or increase microbial oxygen consumption due to organic matter inputs. In soil extracts, DO values were consistently low (0.36-1.5 mg/L), which is characteristic of soil environments where oxygen diffusion is restricted and microbial respiration dominates at the soil-water interface.

Turbidity levels in groundwater samples were generally low (0.6-3.6 NTU) and below the WHO guideline value of 5 NTU, confirming the relatively clear nature of the well water and the absence of significant particulate contamination. In contrast, turbidity values in soil extracts were extremely high (175-550 NTU), particularly in samples C3 and C4. This phenomenon is primarily related to the dispersion of fine clay particles and suspended soil colloids during extraction, rather than direct groundwater pollution. Similar observations have been reported in clay-rich soils where physical disturbance enhances particle suspension.

Total hardness values were high in several groundwater samples (370-1730 mg/L) and markedly elevated in soil extracts (544-3064 mg/L), with samples B4, B5 and all soil extracts exceeding recommended guideline limits. This high hardness is mainly attributed to the dissolution and leaching of calcium and magnesium carbonates from the dominant carbonate lithology of the region. Although high hardness does not pose a direct hazard for irrigation, prolonged use of such water may influence soil permeability and nutrient balance. No consistent relationship was observed between turbidity and hardness, indicating that these parameters are governed by independent geochemical processes.

Soil texture analysis demonstrated substantial spatial variability across the study area. Samples B1 and B5 were classified as sandy clay loam, B2 as loam, B3 as silty loam with a relatively high clay fraction and B4 as clay loam, as confirmed using the USDA soil texture triangle. The dominance of clay-rich textures in several locations is likely linked to Euphrates floodplain deposits, characterized by fine sediments, low permeability and poor drainage. Nevertheless, soils from the Saqlawiyah area exhibited relatively better structure and fertility compared with other locations, enhancing their suitability for crop growth. Elevated cation exchange capacity (CEC), particularly in the clayey soils of Al-Halabsa and Al-Karma, enhances nutrient retention but may also increase the potential for accumulation of contaminants and heavy metals.

Sodium adsorption ratio (SAR) values were low (0.189-0.599), indicating an absence of sodicity hazards and favorable conditions for maintaining soil structure under irrigation. Calcium was the dominant cation, followed by magnesium and sodium, a distribution that supports soil aggregate stability. Anion concentrations were generally within acceptable ranges; however, elevated bicarbonate levels in samples B2 and B4 may, over prolonged irrigation periods, alter soil chemical equilibrium and nutrient availability.

Nitrate concentrations (1-15 mg/L) remained well below the WHO guideline limit, yet the relatively higher nitrate level in sample B3 suggests localized anthropogenic influence, most likely from fertilizer application or agricultural runoff. Although current levels do not pose a critical risk, continued inputs could increase contamination potential over time. Phosphate concentrations were low (0.08-1.60 mg/L); nevertheless, sustained fertilizer use may lead to gradual enrichment of soil and groundwater systems.

Trace elements, including boron, cadmium and lead, were detected at concentrations below WHO permissible limits, indicating no immediate environmental or health concern. Overall, groundwater in the Fallujah region can be considered generally suitable for irrigation. However, site-specific variability, combined with elevated hardness, bicarbonate levels and localized anthropogenic influences, highlights the need for continuous monitoring, improved drainage practices and rational fertilizer management to ensure long-term agricultural sustainability and environmental protection.

CONCLUSION

This study evaluated the suitability of groundwater from five wells in Fallujah City, Iraq, for agricultural irrigation through an integrated assessment of physicochemical properties of well water and soil extracts. The results demonstrated that most measured parameters, including pH, EC, TDS, major cations, sodium adsorption ratio and trace metals (Pb and Cd), generally complied with international guideline limits, indicating that the investigated groundwater is largely suitable for irrigation under current conditions.

Despite the overall acceptable water quality, elevated total hardness and bicarbonate concentrations observed in some wells, together with high turbidity and mineral content in soil extracts, highlight site-specific hydrogeochemical constraints that may influence soil properties under long-term irrigation. Furthermore, the presence of measurable nitrate, phosphate and boron concentrations-although below critical thresholds-suggests localized anthropogenic influences, likely related to agricultural practices and wastewater infiltration, which could pose future contamination risks if not properly managed.

Accordingly, continuous and systematic monitoring of groundwater quality is recommended, with particular emphasis on salinity indicators, nutrient dynamics and trace elements. Improving drainage systems and promoting rational fertilizer use are essential measures to prevent soil degradation and safeguard groundwater resources. These actions will support sustainable agricultural development and long-term environmental protection in the Fallujah region.

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Disclaimers

This article was exclusively written by the authors. The opinions expressed are not necessarily those of their institutions.

Informed consent

There were no human or animal subjects in this study. All sampling and laboratory works were carried out according to environmental and lab safety rules.

Conflict of interest

No funding sources had a direct influence on the conduct or publication of this article and the authors disclose no conflicts of interest.

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