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Status and Behavior of Sodium and Magnesium during Leaching of Local and Non-Saline Soils

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Author's contribution

The sole author designed, analysed, interpreted and prepared the manuscript.

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Abstract

Two different sites in northern Iraq (Bashiqa and Hawija) were selected based on their varying rainfall patterns and land use characteristics. Soil samples were collected from the topsoil (0-30 cm) of the study sites, and undisturbed natural soil columns were taken to the same depth (0-30 cm) and with a diameter of 8 cm Three samples per site. Well water and Tigris River water samples were also collected from the same study areas. A laboratory experiment based on miscible displacement was conducted. The soil columns were moistened with Tigris River water and well water to a pore volume of one (PV 1). The moistening and drying process was repeated every ten days until the pore volume reached ten (PV 10). The soil columns were then washed using intermittent leaching after the completion of the moistening and drying cycles for each type of water (Tigris River water and well water) used for moistening and leaching. The results showed that the salt concentration increased at both study sites after the completion of ten wetting and drying cycles. The electrical conductivity values increased to (1.30 - 10.3) dS m^{-1} at the Bashiqa and Hawija sites when using river water, respectively. However, when using well water, the electrical

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conductivity values increased to (3.4 - 17.8) dS m^{-1} at the Bashiqa and Hawija sites, respectively. The results also showed that the amount of aggregated magnesium was higher than the amount of sodium in both cases, whether using river or well water. Furthermore, the results indicated that the release velocity coefficient for sodium was higher than that of magnesium, according to the power function equation. The leaching process using river water was initially rapid, accompanied by a rapid decrease in the electrical conductivity of the effluent and an increase in pore volume at both study sites (Bashiqa and Hawija) up to pore volume 8, at which point the leaching curve stabilized and the slope ended. This indicates the dissolution of all easily soluble salts and most of the trace salts. The solubility, however, the path of the leaching curve using well water behaved differently at the site (Bashiqa), where the leaching path curve rose. This indicates a rise in the concentration of salts at the site during the leaching process instead of a decrease. The reason for this is that the well water has a high concentration of salts (3.5 dS m^{-1}). At the site of Hawija, the values of electrical conductivity decreased slightly, which is considered insufficient because the value of electrical conductivity did not reach the critical limit at which the soil is considered non-saline (4 dS m^{-1}).

Keywords: Sodium and magnesium; well water; river water; soil salinity; leaching process.

1. Introduction

The ionic and salinity composition of irrigation water affects the quantity and quality of ions in the soil solution. Irrigation water contains a quantity of dissolved ions, including basic cations, which participate in cation exchange. The irrigation process causes the precipitation or release of these ions depending on their ionic composition. The ion with the highest concentration in the irrigation water dominates the exchange surfaces of soil colloids, thus affecting the availability and absorption of other ions. The properties of irrigated soil are affected by the quality and ionic composition of the irrigation water and consequently, its availability to plants (Alhadede *et al.,* 2022), stated (Rengasamy, 2018) that the dissolution of salts and minerals increases and the intensity of weathering increases with the increase in the ionic strength of water, and that the increase in the ionic strength of water directly affects the rate of dissolution of carbonate minerals and the release of ions into the soil solution. That is, the ionic strength of water will affect the dissolution of ion-bearing minerals and salts, and thus affect the rate of their dissolution and change the ionic composition of the soil solution.

Giving these ions a chemical attention is required to identify the state and behavior of their various reactions that occur in the soil system, such as adsorption, release, dissolution, precipitation, oxidation, and reduction between the liquid and solid phases of the soil. This is because the dynamic equilibrium state of these ions is based primarily on the concept of ion or cation exchange and the chemical and salt composition of the equilibrium solution is greatly affected by the ionic strength of the solutions that make it up. Researchers have conducted numerous studies to predict the effect of varying water ionic strength on the chemical composition of the liquid phase represented by the equilibrium solution (Farahmand et al., 2009 and Ahmed et al., 2018). Sodium ions are important and reliable ions in evaluating irrigation water, due to their effect on some physical properties of the soil. They work to disperse soil particles and aggregates, which causes a decrease in water conductivity, poor aeration, and an increase in the apparent density of the soil, which reduces the availability of nutrients to the plant (Morari et al., 2021). Magnesium ions have a negative effect, twice that of calcium ions. Therefore, exchange surfaces containing exchangeable magnesium ions tend to absorb more water than exchangeable calcium ions, which weakens the forces that keep soil particles together, leading to increased swelling and dispersal of clay. In general, the effect of divalent positive ions on soil properties is less than that of monovalent ions (Haviln, 2020).

Given the risks of salinity, which has recently begun to spread towards the northern regions of Iraq due to the lack of rainfall, as most of the agricultural lands in Iraq are located within the arid and semi-arid regions that depend on irrigation, there is a need to study the reactions in systems containing basic positive ions in some soils of northern Iraq, including to show the extent of the effect of the ionic strength of irrigation water, especially well water that has been widely used for irrigation. Based on the above, this study came with the aim of knowing the effect of the ionic strength of irrigation water on the release of sodium and magnesium ions and studying the path of the kinetic reaction of basic positive ions with a mathematical description using one of the kinetic equations.

2. Materials and Methods

Two different sites in northern Iraq (Bashiqa, Hawija) were chosen based on the difference in rainfall range and land use. Soil samples were collected from the surface layer (0-30 cm) of the soils at the study sites. Undisturbed natural soil columns were taken to the same depth (0-30 cm) and diameter (8 cm) with three replicates for each site, whose geographical locations are recorded in Table 1. After the samples arrived at the laboratory, they were air-dried and then ground using a wooden mallet. They were sieved through a sieve with openings of (2 mm) and stored inside plastic containers to prepare them for various laboratory analyses and studies. Well water and Tigris River water samples were taken from the same study areas.

2.1 Laboratory Analyses

Chemical and physical analyses were performed on soil samples in the laboratories of the Department of Soil Science and Water Resources, College of Agriculture and Forestry, University of Mosul. The degree of reaction was measured using a pH meter and electrical conductivity using an EC meter. The cations of calcium and magnesium were determined by titration with ferric acid (0.01)M, and sodium and potassium using a flame photometer. Chloride ions were determined by titration with silver nitrate (0.01)M, and carbonates and bicarbonates by titration with dilute sulfuric acid (0.01)M, while sulfates were determined by precipitation using barium chloride. Soil texture was measured using a hydrometer and apparent density by the paraffin wax method. Soil organic matter was calculated by wet oxidation using potassium dichromate (1M), and calcium carbonate by titration with a 1M NaOH solution. The cation exchange capacity (CEC) was determined by saturation with an acetate solution. Sodium at a concentration of (1M), gypsum was measured by the acetone precipitation method as shown in Tables 2,3 according to the methods mentioned in Salem and Ali (2017).

2.2 Chemical Analysis of Water Samples (River, Well)

The chemical properties of the well water samples used in the study were estimated, including (degree of reactivity, electrical conductivity and positive and negative dissolved ions) according to the methods mentioned in Salem and Ali (2017) and classified according to the American salinity laboratory (Richard,1954) as shown in Table 4.

Table 1. Soil sampling locations and GPS coordinates for the study

Location	Latitude	Longitude	Elevation
Bashiqa	36.470495	43.253222	297
Hawija	53.275536	43.889397	191

Table 2. The concentration of dissolved ions in the soil samples of the study

Location	pH	EC	Ca^{+2}	Mg^{+2}	Na^{+}	K^{+}	Cl^{-}	HCO_3^{-}	SO_4^{-2}
		dS m^{-1}				meq l^{-1}			
Bashiqa	7.40	0.53	2.60	2.40	0.50	0.10	0.60	3.0	2.0
Hawija	7.38	5.60	20.50	13.5	18.70	0.50	18.20	6.7	28.3

Table 3. Some physical and chemical properties of the study soil samples

Location	O.M	$CaCO_3$	$CaSO_4$	Pb	CEC	Clay	Silt	Sand	Textuer	PV
		g k^{-1}		µg m^3	Cmol kg^{-1}			g k^{-1}		ml
Bashiqa	13.50	465	3.30	1.50	23.80	401	450	149	Si-C-L	224
Hawija	14.80	280	23.8	1.60	22.90	262	462	276	L	205

Table 4. Some chemical properties of well water samples used in the study

Water quality	EC	pH	I mol.l^{-1}	Ca^{+2}	Mg^{+2}	Na^{+}	K^{+}	Cl^{-}	HCO_3^{-}	SO_4^{-2}	SAR	class
	dS m^{-1}		x 10^{-2}				meq l^{-1}					
River water	0.6	7.2	0.78	3.0	2.2	0.70	0.12	1.5	3.2	1.2	0.4	C_2-S_1
well water	3.5	7.3	4.55	13.5	18.5	17.4	0.30	10.0	2.0	19.8	4.3	C_4-S_1

2.3 Kinetic Approach

This approach was used to describe the release behavior of sodium and magnesium ions over time as a kinetic parameter under the influence of water with different ionic strengths (0.0078, 0.0455) mol L^{-1} (River water, well water) respectively. A laboratory experiment based on miscibility displacement (Sparks, 2017) was conducted using natural soil columns. The soil columns were moistened with (Tigris River water, well water) via capillary action and left to equilibrium for 24 hours. The following day, water equivalent to one pore volume (PV1) was added to each soil column. This process was repeated every ten days until the tenth pore volume (PV10) was reached. The soil columns were washed using intermittent leaching. After ten cycles of moistening and drying, the filtrate was collected for each pore volume and for each type of water (Tigris River water, well water) used for moistening and leaching. At the end of the experiment, ten extracts were obtained for each treatment. The electrical conductivity, degree of reactivity, and concentration of ions (sodium, magnesium, calcium, and potassium) of the effluents exiting the leaching columns are measured.

2.4 Calculations

1- Calculate the effect of pore size on the aggregate concentration of dissolved sodium and magnesium.

The rate of release is determined by the power function equation, due to the ability of this equation to better study the fast and slow release phases, considering the washing time or the contact time of the solution as a function of the release of ions.

$$LnC_t = LnC_o + KLnt \qquad (1)$$

Where:
Co = Concentration at time zero
Ct = Washable concentration at time t
K = Leaching rate coefficient for each equation
t = Time (minutes)

2- Calculate the rate of reaction (release) of sodium and magnesium.
3- Calculate the effect of pore size on the electrical conductivity values in terms of (ECt/ECo) of the discharge.

3. Results and Discussion

The results shown in Table 5 indicate the soil reactivity, electrical conductivity, and ion concentrations of sodium, magnesium, calcium and potassium in the leachate from the two study sites using river water and well water. The results show that the salt concentration increased at both study sites after the completion of ten wetting and drying cycles. The electrical conductivity values rose to (1.30 - 10.3) dS m^{-1} at the Bashiqa and Hawija sites when using river water, respectively. When using well water, the electrical conductivity values rose to (3.4 - 17.8) dS m^{-1} at the Bashiqa and Hawija sites, respectively, compared to the salt concentrations at the two sites before the completion of the wetting and drying process. The electrical conductivity values, as shown in Table 2, were (0.53) dS m^{-1} at the Bashiqa site and (5.60) dS m^{-1} at the Hawija site. The reason for the increased concentration is... The salts in the two study sites are the dissolution of salts deposited in the soil in succession without leaching them from the soil columns, and thus their accumulation and high concentration due to the lack of suitable drainage conditions and leaching the salts from the soil and removing them (Zhao et al., 2023). When the leaching process was completed up to the tenth pore size, we note that the values of electrical conductivity decreased to (0.6) dS m^{-1} in the Bashiqa site and to (6.8) dS m^{-1} in the Hawija site respectively when using river water. However, when using well water in the leaching process, we note that the leaching process followed the opposite path of the leaching process using river water, as the concentration of salts increased to (4.2) dS m^{-1} in the Bashiqa site, and decreased slightly to (16.1) dS m^{-1} in the Hawija site.

The increased electrical conductivity values after completing the leaching process using well water are due to the high concentration of the main cations that contribute to soil salt formation, most importantly sodium and magnesium ions. These ions contribute to the formation of highly soluble salts, which in turn increase the osmotic pressure of the soil. They have a negative impact on soil structure and clay dispersion, thus reducing water permeability and the soil's ability to retain water (Rengasamy et al., 2018). Table 5 shows that the sodium and magnesium ion concentrations at the Bashiqa site increased to (2.9 - 4.5) meq l^{-1} respectively when using river water, and increased to (13.4 - 10.8) meq l^{-1} respectively when using well water. At the Hawija site, the sodium and magnesium concentrations increased to (28.6 - 33.7) meq l^{-1} respectively when using river water, and increased to (71.6 - 44.2) meq l^{-1} respectively when using well water. When using well water, the sodium and magnesium concentrations decreased to (1.3 - 2.0) meq l^{-1} respectively after the leaching process was completed and up to the 10th pore size, as shown in Table 5. At the Bashiqa site, the sodium and magnesium concentrations decreased to (15.2 - 22.2) meq l^{-1} respectively when using river water, while when using well water, the concentrations increased to (14.7 - 13.3) meq l^{-1} respectively. At the Hawija site, the sodium and magnesium concentrations decreased to (32.4 - 54.6) meq l^{-1} respectively when using river water, while when using well water, the concentrations decreased slightly to (32.4 - 54.6) meq l^{-1} respectively. This can be explained by the fact that well water already contains dissolved salts, and when used for leaching, an ionic balance is not achieved between the soil solution and the leaching water. A sufficient concentration difference is created to push the salts out of the soil bed, while the river water keeps the system in equilibrium, allowing the salts to continue to dissolve and move out of the soil bed and creating a large concentration difference and acting as a medium that washes the salts out of the soil more efficiently These results are consistent with what was obtained (Hoshan, 2022; Author, 2024).

Table 5. Some chemical properties of leachate from river water used in the two study sites of Bashiqa and Hawija

PV	Time min	Bashiqa						Time min	Hawija					
		pH	EC dS m^{-1}	Na^+	Mg^{+2}	Ca^{+2}	K^+		pH	EC dS m^{-1}	Na^+	Mg^{+2}	Ca^{+2}	K^+
				meq l^{-1}							meq l^{-1}			
	River water													
1	62	7.4	1.3	2.9	4.5	4.4	0.15	75	7.5	10.3	28.6	33.7	38.5	0.20
2	142	7.4	1.2	2.7	3.5	4.3	0.15	155	7.4	10.2	24.4	32.2	41.1	0.18
3	222	7.4	1.1	2.5	3.2	4.2	0.13	260	7.4	9.7	23.6	32.0	38.5	0.18
4	307	7.4	1.0	2.3	3.0	4.3	0.12	347	7.5	9.7	23.4	32.4	38.0	0.16
5	397	7.3	0.9	2.2	2.8	3.1	0.13	425	7.5	9.6	22.7	31.1	38.1	0.17
6	497	7.5	0.8	2.1	2.5	2.9	0.10	595	7.6	8.7	19.8	30.4	35.5	0.16
7	607	7.5	0.8	1.8	2.3	2.6	0.10	715	7.7	7.2	17.7	27.6	31.2	0.15
8	727	7.5	0.7	1.6	2.2	3.1	0.11	856	7.6	7.1	16.2	25.3	29.3	0.14
9	877	7.5	0.6	1.5	2.1	2.3	0.10	992	7.7	6.9	15.8	22.4	25.5	0.13
10	1027	7.6	0.6	1.3	2.0	2.2	0.10	1215	7.7	6.8	15.2	22.2	24.4	0.12
	well water													
1	76	7.4	3.4	13.4	10.8	11.5	0.17	91	7.5	17.8	44.2	71.6	65.7	0.50
2	161	7.4	3.5	13.0	11.6	12.7	0.16	182	7.6	18.1	42.3	71.2	66.3	0.45
3	280	7.5	3.6	13.8	11.9	12.8	0.14	314	7.5	18.0	42.1	70.6	67.6	0.30
4	406	7.6	3.7	14.2	12.1	13.4	0.13	512	7.7	17.2	41.2	67.8	64.6	0.30
5	541	7.6	3.8	14.3	12.0	13.5	0.13	616	7.5	17.1	40.7	64.2	63.5	0.28
6	686	7.7	3.9	14.5	13.4	14.8	0.11	792	7.6	16.8	38.6	62.4	61.7	0.25
7	836	7.7	4.0	14.6	13.8	13.9	0.10	991	7.7	16.5	37.4	60.6	61.3	0.25
8	1002	7.6	4.1	14.6	13.8	14.8	0.11	1181	7.5	16.4	36.2	57.4	60.5	0.24
9	1176	7.7	4.2	14.7	13.2	14.9	0.10	1316	7.4	16.2	35.6	55.4	60.2	0.23
10	1327	7.7	4.2	14.7	13.3	14.9	0.10	1515	7.4	16.1	32.4	54.6	60.3	0.22

3.1 Calculating the Effect of Pore Size on the Aggregate Concentration of Dissolved Sodium and Magnesium

Figs. 1, 2 show the aggregate release pathway of sodium and magnesium resulting from the leaching of undisturbed soil columns using river water and well water across ten pore sizes using the intermittent leaching method. The results showed variation in the aggregate sodium and magnesium amounts obtained from the studied sites as a result of the intermittent leaching process up to the tenth pore size. We observe from the results obtained in Figs. 1, 2 that the aggregate magnesium amount was higher than the sodium amount in both cases, whether using river or well water. This can be explained by the fact that the alternating wetting and drying process and intermittent leaching affect the mechanism of changes occurring in magnesium (Shi & Xia, 2024). The higher cumulative amount of magnesium compared to sodium after leaching is attributed to the high solubility of magnesium salts and their ease of displacement from the exchange complex and movement within the soil pores, in contrast to the relative retention of sodium on clay colloids. Furthermore, magnesium is more easily displaced with increasing leaching power and the presence of calcium with decreasing solution power. The ionizing (El Ramady et al., 2024), as shown in Figs. 1, 2, indicates that the aggregate concentration of sodium and magnesium was higher when using well water compared to using river water. This is due to the dissolved concentrations of sodium and magnesium added to the soil when using well water, compared to river water, which has low salinity and is a renewable source with the ability to continuously reduce salts. When using well water, it adds new salts with the leaching water, thus compensating for the sodium and magnesium concentration that was washed away or increasing the sodium and magnesium concentration in the soil solution instead of reducing it These results are consistent with what was obtained (Ghanim & Alhadede, 2022 and Zhao et al., 2025).

3.2 Calculating the Rate of Reaction (Release) Coefficient for Sodium and Magnesium

The concept of reaction rate (release rate) is defined as the rate of change in the concentration of reactants or products as a function of time. Based on this concept, it was applied to the soils of the study sites to determine the release rate of sodium and magnesium according to the power function equation. Figs. 3, 4 illustrate the release process and the release rate coefficient. The results showed the values of the release rate coefficient according to the power function equation. The release rate coefficient for sodium treated with river water ranged between (0.2955 – 0.2314) meq kg min^{-1}, while the release rate for magnesium in the same treatment ranged between (0.2613 – 0.1689) meq kg min^{-1} in the soils of the two study sites (Bashiqa and Hawija), respectively. The release rate for sodium treated with well water ranged between (0.0361 – 0.1028) meq kg min^{-1}, while the release rate for magnesium in the same treatment ranged between (0.0612 – 0.1121) meq kg min-1 in the soil of the two study sites (Bashiqa, Hawija) respectively.

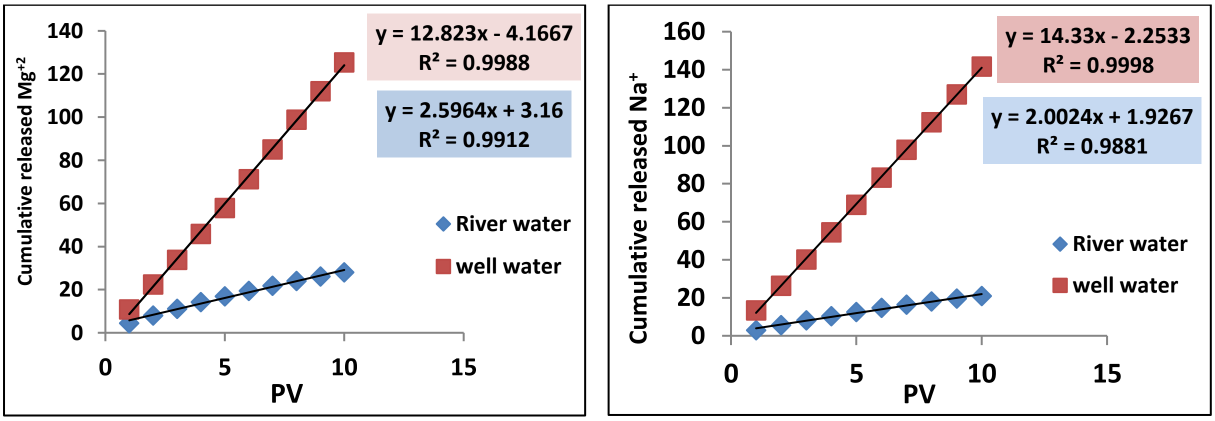

Fig. 1. The release pathway of sodium and magnesium during the leaching process at the Bashiqa site

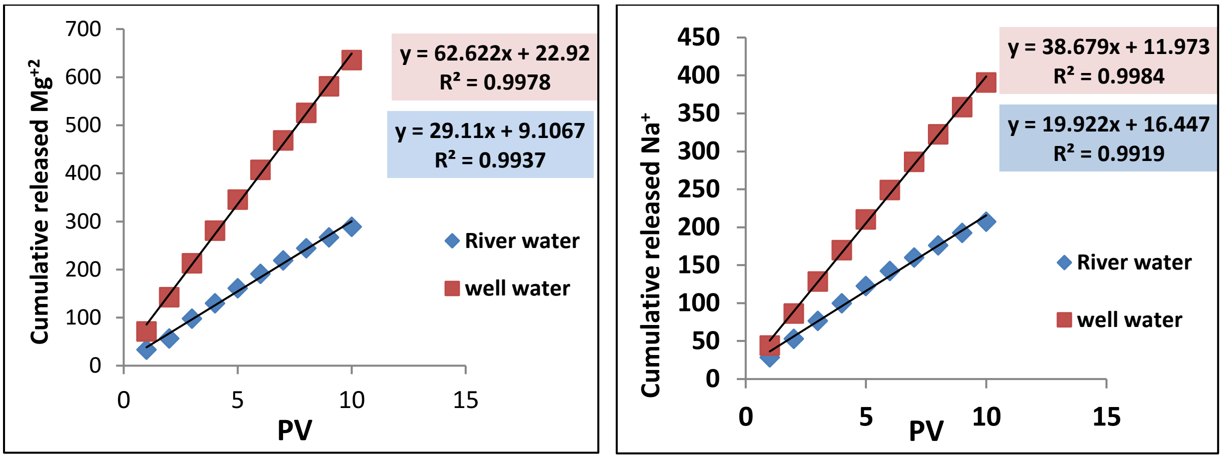

Fig. 2. The release pathway of sodium and magnesium during the leaching process at the Hawija site

The results showed that the release rate coefficient for sodium was higher than that for magnesium. The difference in the release rate coefficients of sodium and magnesium in the studied soils can be explained by variations in soil clay and organic matter content, sodium and magnesium formulations, as well as the electrical conductivity and adsorption capacity of monovalent sodium and divalent magnesium ions on soil particles and organic matter. These factors are significant in determining the release of the ion based on its binding energy to the soil solid phase. This clearly indicates that the intermittent leaching process allowed for the release of more washed salts, thus demonstrating the efficiency of intermittent leaching in the leaching process. These results are consistent with what was obtained.

3.3 Calculating the Effect of Pore Size on Electrical Conductivity Values in Terms of (ECt/ECo) of the Outgoing Discharge

Fig. 5 shows the change in the electrical conductivity of the effluent (ECt/ECo) ratio with pore volume using the intermittent leaching method. The leaching process using river water was initially rapid, accompanied by a rapid decrease in the electrical conductivity of the effluent and an increase in pore volume at the two study sites (Bashiqa and Hawija). The leaching curve exhibited a continuous slope to the eighth pore volume, where the curve stabilized and the slope ceased. This indicates the dissolution of all easily soluble salts and most of the sparingly soluble salts. This may be attributed to the ten-day leaching pause, which allowed for a longer dissolution period for the sparingly soluble salts, thus reducing salt concentration and the electrical conductivity. Using river water in the leaching process helps restore the concentration difference, dissolve the salts, and wash them out of the soil. These results are consistent with those of (Li et al., 2023). However, the leaching curve using well water exhibited a different behavior at the (Bashiqa) site. The path of the leaching curve increased, and this shows that the concentration of salts at the site increased during the leaching process instead of decreasing. The reason for this is that the well water has a high concentration of salts (3.5 dS m^{-1}) as shown in Table 4, and that the continuous addition of well water with a high salt content led to an increase in the electrical conductivity (EC) values of the soil compared to the soil to which low-salinity river water was added. This increase is attributed to the repeated addition of dissolved salts with water, which contains high concentrations of soluble ions, especially (sodium, magnesium, calcium and chloride), which leads to an increase in the concentration of salts in the soil solution with repeated water additions. The leaching process with the same well water, which works to re-dissolve the salts in the soil, contributed to this, in addition to the negative effect of sodium, which works to disperse soil particles and thus reduce water permeability within the soil, which limits the efficiency of leaching salts. As for the Hawija site, the values of electrical conductivity decreased slightly, which is considered insufficient because the value of electrical conductivity did not reach the critical limit at which the soil is considered non-saline (4 dS m^{-1}). These results are consistent with (Gharaibeh et al., 2014 and Ding et al., 2023).

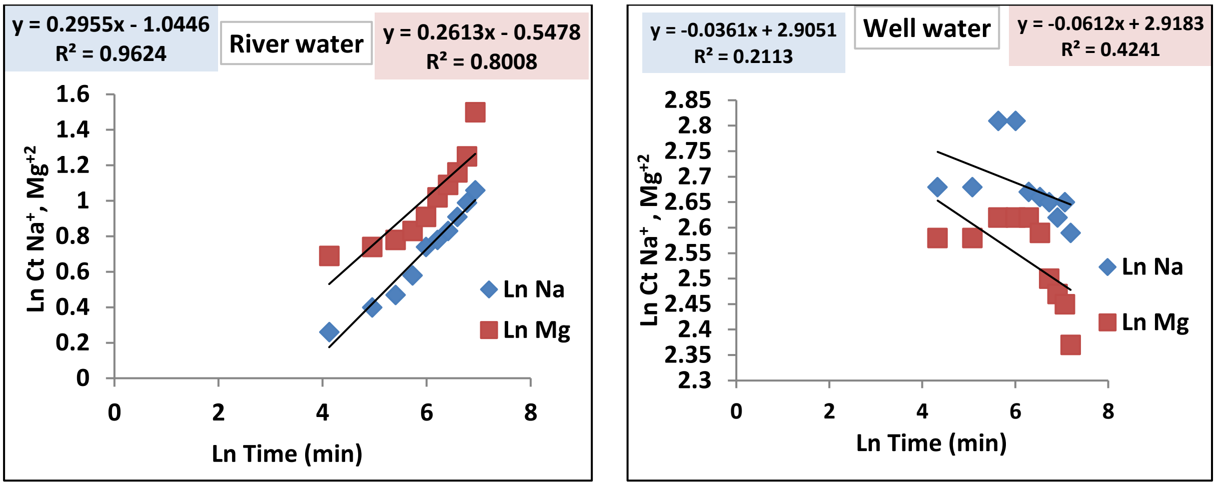

Fig. 3. The logarithmic relationship between (Na^+, Mg^{+2}) and time for river and well water at the Bashiqa site

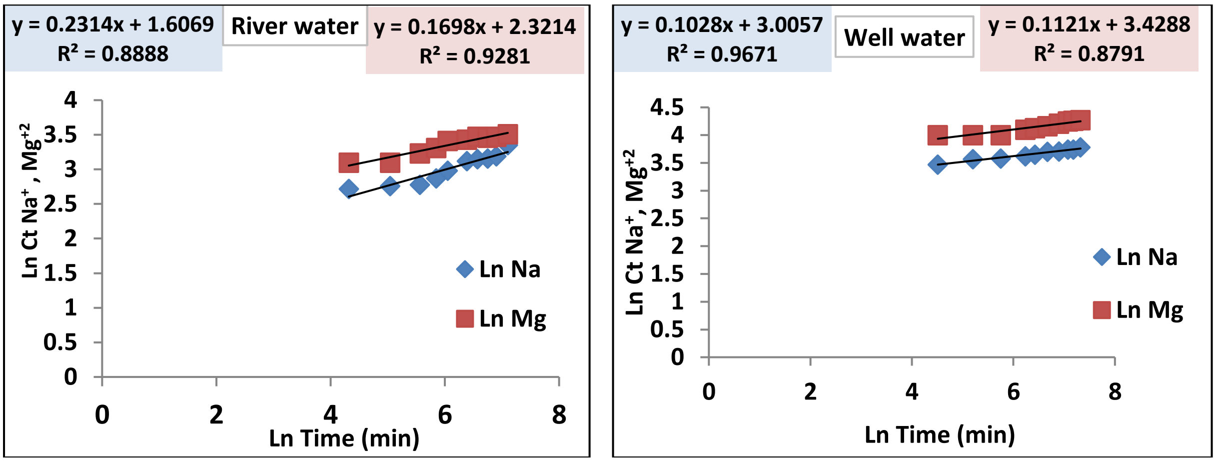

Fig. 4. The logarithmic relationship between (Na^+, Mg^{+2}) and time for river and well water at the Hawija site

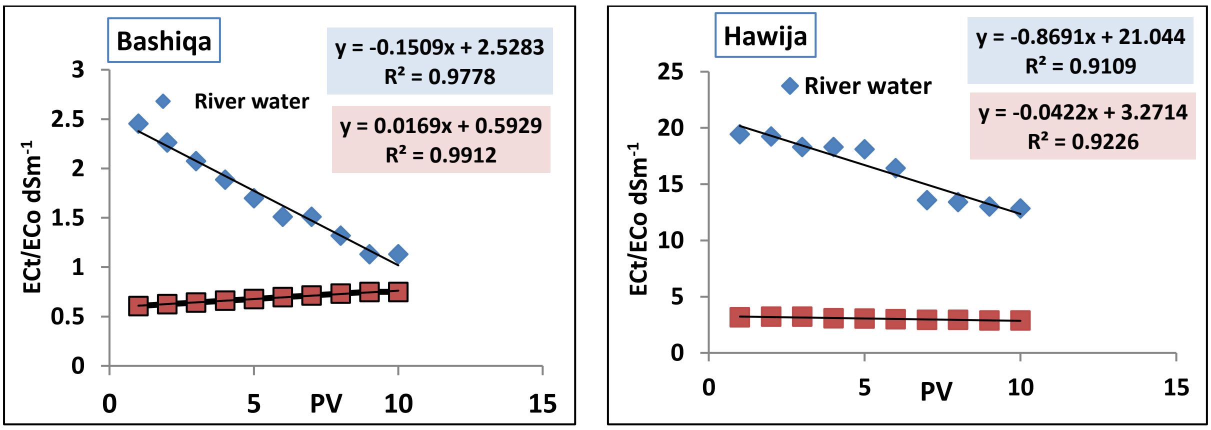

Fig. 5. Effect of pore size on electrical conductivity values in terms of (ECt/ECo) for the outgoing discharge

4. Conclusions

Using river water in the wetting and drying process had a lesser effect on raising the values of electrical conductivity and sodium and magnesium concentration than well water in the soils of the study sites. The release rate coefficient for sodium was higher than the release rate coefficient for magnesium, but the amount of magnesium that was released or leaching away was higher than the amount of sodium. Using river water in the washing process works to restore the concentration difference and dissolve the salts and wash them out of the soil surface, and its efficiency in the washing process is better than well water, which led to an increase in the concentration of salts during the washing process, This study can be considered as a source for conducting further studies on soils with different electrical conductivity and well water with different or more different salt concentrations to study and understand the behavior of sodium and magnesium ions or other ions.

Disclaimer (Artificial Intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

Competing Interests

Author has declared that they have no known competing financial interests or non-financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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