

Effects of Irrigation with Agricultural Drainage Water on Soil Physical and Chemical Properties in a Semi-Arid Region

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ABSTRACT

Water scarcity in semi-arid regions has increased interest in reusing agricultural drainage water for irrigation; however, its impacts on soil systems require quantitative evaluation under field-representative conditions. This study investigated the effects of two years of irrigation with agricultural drainage water on soil physical and chemical properties under semi-arid conditions in southeastern Türkiye within the Southeastern Anatolia Project (GAP) irrigation network. A lysimeter-based experiment under field-representative environmental conditions was conducted using agricultural soils collected from cultivated lands and exposed to natural climatic variability. Four irrigation treatments were applied: freshwater (control), untreated agricultural drainage water, treated drainage water, and mixed drainage water. Soil samples were collected at depths of 0-30 and 30-60 cm after the second irrigation season. Soil physical properties (texture, bulk density, and water retention characteristics) and chemical properties (pH, electrical conductivity, exchangeable cations, cation exchange capacity, and exchangeable sodium percentage) were analyzed using standard methods. Soil physical properties showed only minor treatment- and depth-related variations, with no substantial deterioration in bulk density or available water content. In contrast, soil chemical parameters responded more sensitively to irrigation water quality. Electrical conductivity increased from initial values of 810-1000 $\mu\text{S cm}^{-1}$ to 820-1860 $\mu\text{S cm}^{-1}$ after two years, with the highest value observed in the 0-30 cm layer under untreated drainage water. Across treatments, EC values were generally higher in the 0-30 cm layer, indicating preferential accumulation of surface salts under semi-arid conditions. Exchangeable sodium percentage increased in drainage water-irrigated soils, particularly under untreated drainage water, indicating the onset of sodicity-related processes. Although measured values remained below critical thresholds during the study period, depth-dependent increases in salinity and sodium-related parameters represent early indicators of potential soil degradation. The results suggest that short-term reuse of agricultural drainage water may be feasible, provided that continuous monitoring of soil salinity and sodicity is implemented to ensure long-term soil quality in semi-arid environments.

Keywords: agricultural drainage water, soil salinity, sodicity, semi-arid regions, soil quality.

INTRODUCTION

I ncreasing water scarcity is one of the most critical challenges to agricultural sustainability, particularly in semi-arid and arid regions. Agriculture remains the dominant consumer of freshwater resources worldwide, and the pressure on available water supplies is further intensified by climate variability, population growth, and the expansion of irrigated agriculture. In this context, the reuse of non-conventional water resources, including agricultural drainage water, has emerged as an essential alternative to alleviate water

shortages (Ayers and Westcot, 1985; Qadir et al., 2010). However, while the reuse of drainage water may contribute to water conservation, its potential impacts on soil systems require careful evaluation to ensure long-term land productivity and environmental protection.

Large-scale irrigation projects often generate substantial drainage volumes due to intensive and sometimes inefficient irrigation practices. Türkiye's Southeastern Anatolia Project (GAP) is one of the most extensive regional development and irrigation initiatives in the world, aiming to enhance

agricultural production and socio-economic development in the country's southeastern region. At the core of GAP lies the Atatürk Dam, Türkiye's largest dam, which supplies irrigation water to Şanlıurfa and surrounding provinces through an extensive canal network. While this system has significantly increased irrigated agricultural areas, it has also led to substantial drainage of agrarian water, particularly in the Harran Plain and adjacent irrigated lands (Kendirli et al., 2005; Akın and Şimşek, 2021).

Agricultural drainage water originating from GAP irrigation schemes is increasingly reused by farmers, especially during periods of water scarcity. Such waters typically contain elevated levels of dissolved salts and nutrients, which may harm soil physical and chemical properties when repeatedly applied (Feizi et al., 2010; Rengasamy, 2010; Minhas et al., 2015). Previous studies have primarily focused on the quality assessment of drainage or wastewater used for irrigation, whereas most experimental investigations have been short-term and water-oriented. In contrast, the combined evaluation of soil physical and chemical responses under medium-term irrigation with drainage water remains limited, despite soil being the primary receptor and regulator of irrigation-induced changes.

Soil responses to irrigation with drainage water are highly dependent on local climatic conditions, soil characteristics, and irrigation management practices. Semi-arid regions are particularly vulnerable to salinity and sodicity development due to high evapotranspiration rates and limited natural leaching (Rhoades et al., 1992; Oster and Jayawardane, 1998). Changes in soil salinity, exchangeable sodium levels, pH, and related physical properties can directly affect soil structure, water movement, and overall soil quality. Therefore, understanding how repeated irrigation with drainage water alters soil properties under real field or near-field conditions is essential for evaluating the sustainability of drainage water reuse in irrigated agricultural systems.

The present study aims to evaluate the effects of two years of irrigation with agricultural drainage water on soil physical

and chemical properties in a semi-arid region of Türkiye. Drainage water used in the experiment was collected from agrarian drainage channels in Şanlıurfa, which receive return flows from irrigated lands supplied by the Atatürk Dam. The study focuses specifically on soil responses, whereas the treatment processes used to produce different irrigation water qualities are beyond its scope. By providing experimental evidence from a GAP-supported irrigation environment, this study contributes to a better understanding of the medium-term impacts of drainage water reuse on soil systems and offers insights applicable to other semi-arid regions facing similar water management challenges.

MATERIAL AND METHODS

Study area and experimental setup

The experiment was conducted under semi-arid climatic conditions representative of southeastern Türkiye. The study area is located near Diyarbakır, within the broader influence zone of the Southeastern Anatolia Project (GAP). This region is characterized by hot, dry summers and mild, relatively wet winters, with annual precipitation averaging approximately 487 mm, most of which occurs during winter and early spring. High evapotranspiration rates during the growing season increase the risk of salt accumulation in irrigated soils.

Soils used in the experiment were collected from agricultural lands near the experimental site and are classified as alluvial, fine-textured soils. These soils are classified as first-class agronomic soils, with good natural drainage, no shallow groundwater table, and no inherent salinity or sodicity problems. Before the experiment, the soils exhibited neutral to slightly alkaline pH values (7.8-7.9), low organic matter content, high cation exchange capacity, and low exchangeable sodium percentage.

The study was conducted using a lysimeter-like system comprising cylindrical metal tanks with a diameter of 0.60 m and a depth of 1.00 m. The tanks were installed above ground to allow free air circulation and exposure to natural light and temperature

conditions. To facilitate drainage, a 5 cm layer of gravel-sand mixture was placed at the bottom of each tank, followed by soil packed in 5 cm layers to the previously determined bulk density. The total soil depth in the tanks was approximately 85 cm (Üzen, 2009).

Irrigation water sources

Irrigation water used in the experiment included agricultural drainage water of varying qualities and freshwater. Agricultural drainage water was collected from drainage channels in Şanlıurfa Province that receive return flows from irrigated lands supplied by the Atatürk Dam, Türkiye's largest dam and a key component of the GAP irrigation network. These drainage waters represent typical return flows generated under intensive irrigation conditions in the Harran Plain and surrounding areas.

Different irrigation water qualities were obtained to represent control and drainage water treatments. While certain drainage waters underwent preliminary treatment to achieve contrasting water qualities, the performance and technical details of these processes are beyond the scope of this study. The present work focuses exclusively on the effects of irrigation water quality on soil physical and chemical properties.

Experimental design and irrigation treatments

The experiment was conducted over two consecutive growing seasons (2016-2017) using a randomized design with five replicates per treatment. Four irrigation treatments were applied:

- **I₁**: 100% freshwater (control);
- **I₂**: 100% untreated agricultural drainage water;
- **I₃**: Treated agricultural drainage water;
- **I₄**: A mixture of 50% untreated drainage water and 50% treated drainage water.

Irrigation scheduling was based on regional agronomic practices for cotton cultivation, with irrigation intervals ranging from 8 to 10 days depending on climatic conditions and crop development stages. The amount of irrigation water applied was

determined from Class A pan evaporation data, using each tank's irrigated surface area and the appropriate soil depth.

Soil sampling and analysis

Soil samples were collected at the end of each growing season, after harvest and before the onset of winter rainfall, to assess changes induced by two years of irrigation. Disturbed soil samples were collected from each tank using an auger to represent the overall soil profile, while undisturbed samples were used for selected physical analyses.

Soil texture was determined using the Bouyoucos hydrometer method, and textural classes were identified using the soil texture triangle (Black, 1957). Soil bulk density was calculated based on the mass-to-volume ratio of undisturbed samples. Field capacity and permanent wilting point were determined using a pressure plate apparatus at 1/3 atm and 15 atm, respectively. Soil saturation percentage was measured according to standard procedures (Tüzüner, 1990).

Chemical analyses were conducted on saturated soil paste extracts (Richards, 1954). Soil electrical conductivity (EC) was measured at 25°C using a conductivity meter to determine total soluble salt content (Soil Survey Staff, 1951).

Soil pH was measured in the saturated paste using a glass electrode pH meter (Richards, 1954). Calcium carbonate content was determined using a Scheibler calcimeter (Çağlar, 1949). Exchangeable cations (Ca²⁺, Mg²⁺, Na⁺, and K⁺) were analyzed using standard titrimetric and flame photometric methods (Cheng and Bray, 1951; Reitemeier, 1951). Cation exchange capacity (CEC) and exchangeable sodium percentage (ESP) were calculated from measured exchangeable cation concentrations.

Available phosphorus was determined using the Olsen method, while available potassium was measured following ammonium acetate extraction (Olsen and Sommers, 1982). Soil organic matter content was determined using the Walkley-Black wet oxidation method (Richards, 1954). Selected trace elements and heavy metals (Fe, Zn, Mn, Cu, Cd, Pb, and B)

were analyzed using atomic absorption spectrophotometry following appropriate extraction procedures (Slawin, 1968).

Statistical analysis

Soil physical and chemical data were evaluated using descriptive statistical methods. Mean values were calculated for each treatment and soil depth, and treatment effects were assessed by comparing these means across irrigation treatments and sampling depths. Statistical analysis was used to identify trends and treatment-related changes in soil properties over the two-year irrigation period.

RESULTS AND DISCUSSION

Changes in soil physical properties

Two years of irrigation with agricultural drainage water produced measurable changes in selected soil physical properties compared with the control treatment irrigated with freshwater. The initial soil properties are

presented in Table 1. Soil texture remained unchanged throughout the experimental period, indicating that irrigation water quality did not alter the inherent textural class of the alluvial soils used in the experiment.

As shown in Table 1, the soils were predominantly clayey (C) with high clay content (63.6-67.6%) and low hydraulic conductivity (0.036-0.070 m day⁻¹), reflecting their fine-textured nature. Initial bulk density values ranged from 1.19 to 1.27 g cm⁻³, increasing slightly with depth.

After two years of irrigation, soil bulk density showed slight variations among irrigation treatments. Compared with the control, soils irrigated with untreated and treated drainage waters exhibited modest increases in bulk density, which remained within acceptable limits for agricultural soils. These changes were more pronounced in treatments receiving a higher proportion of drainage water, suggesting that dissolved salts may influence soil structural stability.

Table 1. Selected physical and chemical properties of the soil used in the experiment (Üzen, 2014)

Soil depth (cm)	Sand (%)	Silt (%)	Clay (%)	CaCO ₃ (%)	CEC (cmol kg ⁻¹)	Exchangeable Na (cmol kg ⁻¹)	Bulk density (g cm ⁻³)	Hydraulic conductivity (m day ⁻¹)	pH	Total salt (%)	EC (dS m ⁻¹)
0-30	8.9	27.5	63.6	8.5	34.5	25.6	1.19	0.070	7.9	0.0519	0.81
30-60	9.0	25.4	65.6	8.6	35.2	25.4	1.25	0.044	7.9	0.0646	1.00
60-90	9.0	23.4	67.6	8.6	36.5	27.1	1.27	0.036	7.8	0.0612	0.96

* C: Clay; CEC: Cation Exchange Capacity.

Field capacity and permanent wilting point values showed minor treatment-dependent differences. Soils irrigated with drainage water generally showed slightly higher water retention at both field capacity and wilting point than the control. As a result, available water content did not show substantial reductions across treatments, indicating that short- to medium-term irrigation with drainage water did not severely impair soil water-holding characteristics under the experimental conditions.

Changes in soil chemical properties

The results showed that irrigation with agricultural drainage water had a more pronounced effect on soil chemical properties than on physical characteristics. Soil pH

values remained within the slightly alkaline range across all treatments, with no substantial differences observed between the control and drainage-water-irrigated soils. This indicates that irrigation water quality did not induce significant acidification or alkalization over the two years.

In contrast, soil electrical conductivity (EC) increased noticeably in treatments receiving drainage water. The highest EC values were observed in soils irrigated with untreated drainage water, followed by those irrigated with mixed or treated drainage water. Although EC levels increased relative to the control, they did not reach thresholds associated with severe salinity stress, indicating moderate salt accumulation during the experimental period.

Exchangeable sodium levels and exchangeable sodium percentage (ESP) exhibited apparent treatment-related differences. Soils irrigated with untreated drainage water exhibited higher ESP values than the control, indicating the influence of sodium-rich irrigation water. Treated or mixed drainage water exhibited lower ESP values than untreated drainage water, but remained higher than those of the freshwater control. These findings suggest that drainage water irrigation can initiate sodicity-related changes, even within a relatively short period.

Cation exchange capacity (CEC) remained largely stable across treatments, reflecting the buffering capacity of the fine-textured alluvial soils. However, changes in the relative proportions of exchangeable cations were observed, particularly an increase in exchangeable sodium, accompanied by slight reductions in calcium and magnesium in drainage water treatments.

Soil organic matter content showed no significant decline over the two years and

remained generally low across all treatments, consistent with the initial soil conditions. Available phosphorus and potassium levels varied among treatments but did not exhibit consistent trends attributable solely to irrigation water quality.

Trace elements and heavy metal concentrations in soils remained within acceptable limits for agricultural use. No accumulation trends indicative of contamination were observed in drainage water-irrigated soils relative to the control, suggesting that short-term reuse of agricultural drainage water did not pose a significant risk of heavy metal accumulation under the conditions of this study.

Soil pH, EC, CaCO₃, and Organic Matter Content

The results regarding pH, total salt, EC, CaCO₃, and organic matter content of the experimental soils are given in Table 2. The initial soil pH values ranged between 7.8 and 7.9.

Table 2. Electrical conductivity (EC), total soluble salt, pH, CaCO₃, and organic matter contents of soils at different depths after two years of irrigation

Treatments	Depth of layer (cm)	pH	Total salt (%)	EC ($\mu\text{S cm}^{-1}$)	CaCO ₃ (%)	Organic Matter (%)
I ₁	0-30	7.6	0.040	880	8.22	0.54
I ₁	30-60	7.7	0.050	820	8.71	0.50
I ₂	0-30	7.9	0.065	1860	8.82	0.58
I ₂	30-60	8.2	0.083	1750	8.98	0.49
I ₃	0-30	7.4	0.041	980	8.52	0.36
I ₃	30-60	7.4	0.046	810	8.78	0.33
I ₄	0-30	7.6	0.064	1310	8.87	0.49
I ₄	30-60	7.7	0.058	1240	9.14	0.39

Soil pH values were slightly alkaline, ranging from 7.4 to 8.2. There was no significant change in soil pH before and after the experiment. Throughout the study, pH values did not change significantly due to the high clay and lime content and the associated buffering capacity, as explained by Uyanöz (2000) and Tuna and Bürün (2003). Among the treatments, pH values were relatively higher under treatment I₂. For all treatments, no significant differences in soil pH were observed across soil layers.

However, the 0-30 cm layer had relatively lower pH values than the 30-60 cm layer. The soil pH values were not excessively alkaline in areas irrigated with untreated water, likely due to the short irrigation duration. Soil reactions vary with wastewater pH. Similar results were obtained in studies by Shahalam et al. (1998) and Uyanöz (2000), in which wastewater, whether acidic, neutral, or basic, lowered, raised, or had no effect on soil pH. In soil samples collected before the experiment, EC values ranged from 810 to 1000 $\mu\text{S cm}^{-1}$.

At the end of the experiment, the electrical conductivity (EC) values of the soils ranged between 820 and 1860 $\mu\text{S cm}^{-1}$. The experimental treatments affected the EC values of the soils. Specifically, the highest EC value (1860 $\mu\text{S cm}^{-1}$) was observed in the 0-30 cm soil layer in treatment I₂, where no clean water mixture was applied; instead, raw drainage water was used. The lowest EC value was recorded in the 30-60 cm layer (810 $\mu\text{S cm}^{-1}$) for treatment I₃, in which water treated by reverse osmosis was applied. Examination of the data showed that wastewater and fertilizer applications increased EC. When EC values were reviewed by soil depth, it was found that across all treatments, the 0-30 cm layer had higher EC values than the 30-60 cm layer. This can be explained by the fact that in the Southeastern Anatolia Region, where the research was conducted, the high temperatures and low relative humidity during the summer months cause water deep in the soil to rise and evaporate through capillary action, while the minerals accumulate near the surface.

The magnitude of the increase in soil salinity depends on soil texture and permeability, as well as the salt content of irrigation water, with the upper soil layers most affected. El Hamouri et al. (1996), Reboll et al. (1999), Uyanöz (2000), and Tuna and Bürün (2003) reported that the use of highly saline wastewater increases soil salinity.

In soil samples taken before the experiment, lime content ranged from 8.5% to 8.6%. After harvesting, no significant differences in lime (CaCO_3) content were observed in soil samples from the experiment, regardless of depth or water use. The lowest value was measured in the 0-30 cm soil layer in treatment I₁ (8.22%); the highest value was measured in the 0-30 cm soil layer, known as the accumulation horizon, in treatment I₄ (9.14%). It can be said that using clean irrigation water resulted in the lowest lime content. However, in this study, it was observed that the drainage water slightly increased the lime content of the soils. Uyanöz (2000) reported no significant changes in the CaCO_3 content of soil samples in areas where wastewater from the Konya

Main Drainage Canal was used, depending on depth and wastewater irrigation, and Tuna and Bürün (2003) reported that sewage did not affect the soil lime content.

The organic matter content of the soils is generally relatively low. The highest OM content was obtained from treatment I₂ (0.58%), and the lowest OM content was obtained from treatment I₃ (0.33%). For all experimental treatments, the OM content is higher in the upper layers and decreases with depth (Table 2). This can be considered a significant result. Uyanöz (2000) reported that in areas irrigated with wastewater for many years, organic matter was sufficient or high in the 0-30 cm soil layer. That wastewater use increased the organic matter content.

Phosphorus and Potassium Content of Soils after Experiment

The highest available phosphorus content in soil samples was observed in treatment I₂ at the 0-30 cm depth (6.09 kg da^{-1}). In general, phosphorus content decreased with increasing soil depth. Considering the limit values reported by Olsen and Sommers (1982) for agricultural soils, the low phosphorus content ($<6.1 \text{ kg da}^{-1} \text{ P}_2\text{O}_5$) in almost all treatments is noteworthy. Given that drainage water is relatively rich in nitrogen and phosphorus, an increase in soil phosphorus content under treatment I₂ was expected.

The highest values in the experimental soils ranged between 5.96 and 6.10 $\text{kg da}^{-1} \text{ P}_2\text{O}_5$, which are close to the sufficient levels (6.1-12.2 $\text{kg da}^{-1} \text{ P}_2\text{O}_5$) reported by Olsen and Sommers (1982).

In the experimental treatments, the highest water-soluble potassium content was determined in treatment I₂ at the 30-60 cm depth (149.02 $\text{kg da}^{-1} \text{ K}_2\text{O}$). In contrast, the lowest potassium content was observed in treatment I₁ at the same depth (102.87 $\text{kg da}^{-1} \text{ K}_2\text{O}$). The water-soluble potassium contents of the soil samples were generally high, indicating favorable conditions for plant development (Table 3), consistent with previous findings (Rhoades et al., 1992; Oster and Jayawardane, 1998).

Table 3. Phosphorus (P₂O₅) and potassium (K₂O) contents of soils at different depths at the end of the experiment

Treatments	Depth of layer (cm)	Phosphorus (P ₂ O ₅) (kg da ⁻¹)	Potassium (K ₂ O) (kg da ⁻¹)
I ₁	0-30	3.13	123.18
I ₁	30-60	3.53	102.87
I ₂	0-30	6.09	126.84
I ₂	30-60	5.96	149.02
I ₃	0-30	2.89	116.00
I ₃	30-60	2.98	109.02
I ₄	0-30	4.85	126.84
I ₄	30-60	3.89	116.00

Trace Element and Heavy Metal Content of Soils after Experimentation

The trace element and heavy metal contents of the experimental soils, such as iron (Fe), copper (Cu), zinc (Zn), manganese

(Mn), boron (B), lead (Pb), and molybdenum (Mo), were determined. The trace element and heavy metal contents of the experimental soils are given in Table.

Table 4. DTPA-extractable heavy metal and trace element contents of soils at different depths after two years of irrigation

Treatments	Depth of layer (cm)	Fe (ppm)	Cu (ppm)	Zn (ppm)	Mn (ppm)	B (ppm)	Pb (ppm)	Mo (ppm)
I ₁	0-30	4.74	0.87	0.89	4.32	0.35	6.08	0.87
I ₁	30-60	5.21	0.80	0.69	4.57	0.47	6.05	0.67
I ₂	0-30	5.09	0.89	0.97	4.97	0.49	6.44	0.60
I ₂	30-60	5.98	0.79	1.27	5.08	0.69	6.39	0.87
I ₃	0-30	4.02	0.80	0.89	4.50	0.48	6.28	0.47
I ₃	30-60	3.90	0.57	1.01	5.00	0.39	6.12	0.41
I ₄	0-30	4.89	0.59	0.74	5.01	0.58	6.12	0.58
I ₄	30-60	5.06	0.64	1.16	4.47	0.47	5.68	0.68

The DTPA-extractable (plant-available) Fe content ranged from 3.90 to 5.98 ppm. The highest value was observed in the 30–60 cm layer of treatment I₂, whereas the lowest value occurred in the 30–60 cm layer of treatment I₃. According to the critical limits reported by Follett and Lindsay (1970), sufficient Fe concentrations in agricultural soils range between 2.5 and 4.5 ppm. Based on these reference values, Fe contents in the experimental soils were sufficient in some cases and exceeded sufficiency levels in others. Overall, Fe concentrations increased in several soil layers (Table 4). Similar findings were reported by Kırımhan et al. (1983), Murillo et al. (1989), Gutierrez et al. (1995), Bayraklı and Gezgin (1996), and Uyanöz (2000).

The Cu content of the experimental soils exceeded the critical value of 0.2 ppm reported by Viets and Lindsay (1973). The

highest Cu concentration was detected in treatment I₂ (0.89 ppm), whereas the lowest was observed in treatment I₃ (0.57 ppm). Li et al. (2008) emphasized that copper transport in soils irrigated with wastewater is complex due to interactions with nitrogen, chemical treatments, and plant uptake, often resulting in accumulation in surface layers. Increases in soil Cu following the application of wastes of different origins have also been reported by Sikka and Kansal (1995), Özdemir et al. (2004), and Tuna and Girgin (2005), consistent with the present findings.

The Zn content of the experimental soils ranged from 0.69 to 1.27 ppm. The highest Zn concentrations were observed in treatment I₂ at 30-60 cm (1.27 ppm) and in treatment I₄ at the same depth (1.16 ppm). These values were close to or exceeded the critical range of 0.5-1.0 ppm reported by Lindsay and Norvell (1978). The lowest Zn concentrations were

detected in treatment I₁ at 30-60 cm (0.69 ppm) and in treatment I₄ at 0-30 cm (0.74 ppm). Comparable results have been reported by Mortvedt and Giordano (1975), Gayner and Halstead (1976), Mitchell et al. (1978), Kırımhan et al. (1983), Murillo et al. (1989), Gutierrez et al. (1995), and Bayraklı and Gezgin (1996). Sidle et al. (1976) also reported low Zn contents in soils treated with wastewater.

Manganese contents were generally lower in the 0-30 cm layer and increased with depth across most treatments. The highest Mn concentrations were detected in treatments I₂ (5.08 ppm), I₃ (5.00 ppm), and I₄ (5.01 ppm), whereas the lowest values were observed in treatments I₁ (4.32 ppm) and I₄ (4.47 ppm). These values were below or close to the critical limit of 6 ppm proposed by Sillanpää (1982). Previous studies have indicated that Mn dynamics in wastewater-irrigated soils are complex and may exceed critical levels under certain conditions (Gayner and Halstead, 1976; Mitchell et al., 1978; Kırımhan et al., 1983; Murillo et al., 1989; Gutierrez et al., 1995; Bayraklı and Gezgin, 1996; Uyanöz, 2000). Yakupoğlu et al. (2010) attributed this complexity to reduced Mn solubility with increasing soil pH and possible antagonistic interactions with other elements.

Overall, the results indicate that in soils irrigated with wastewater and wastewater mixtures, DTPA-extractable Fe, Cu, Zn, and Mn levels may range from meeting plant requirements to potentially reaching toxic concentrations.

The boron content of the experimental soils ranged from 0.35 to 0.69 ppm. The lowest boron concentrations were detected in treatments I₁ (0.35 ppm) and I₃ (0.39 ppm). In treatments I₁, I₂, and I₄, boron content increased with depth, whereas in treatment I₃ it decreased with increasing depth (Table 4). Overall, soil boron concentrations remained below the moderately sensitive plant threshold of 1–2 ppm reported by Gemalmaz et al. (1993). The present results are consistent with those of Reboll et al. (1999), who reported that although wastewater contained relatively high boron levels, it did not induce boron toxicity in soils or plants.

Lead (Pb) concentrations in the experimental soils ranged from 5.80 to 6.44 ppm (Table 4). Across all treatments, Pb concentrations generally decreased with increasing soil depth, although depth-dependent variations were observed. The Pb levels detected in the experimental soils exceeded the critical concentration of 5 ppm reported by Çay (2013). These findings indicate the need to cultivate Pb-tolerant crops, avoid edible plant production where appropriate, and take technical precautions during irrigation with drainage water. In addition, the proximity of agricultural fields to highways may contribute to elevated Pb accumulation in soils.

Cadmium (Cd) concentrations remained below regulatory threshold values specified in the Water Pollution Control Regulation, indicating no immediate restriction for irrigation use under the conditions of this study. Molybdenum concentrations remained low and showed no clear treatment-related trends (Table 4).

The results of this study demonstrate that two years of irrigation with agricultural drainage water induced measurable changes in soil chemical properties. In contrast, soil physical characteristics were affected to a lesser extent. This distinction highlights the greater sensitivity of soil chemical indicators to irrigation water quality under semi-arid conditions. It emphasizes the importance of monitoring salinity- and sodicity-related parameters in drainage water reuse practices.

Soil physical response to drainage water irrigation

As indicated by the results presented above, particularly those related to bulk density and water retention characteristics, soil physical properties were only slightly affected by irrigation with agricultural drainage water. The limited changes observed in soil texture, bulk density, and water retention characteristics suggest that short- to medium-term irrigation with drainage water did not lead to severe structural degradation of the alluvial soils used in this experiment. The stability of these parameters indicates that the fine-textured nature of the soils

provided a buffering capacity against rapid physical deterioration. Similar findings have been reported in previous studies conducted under semi-arid conditions, where short-term reuse of saline or marginal-quality irrigation waters did not immediately impair soil physical structure, particularly in soils with high clay content and good natural drainage (Feizi et al., 2010). However, the slight increases in bulk density and saturation-related parameters observed under drainage water treatments may represent early structural adjustments associated with salt accumulation. Although these changes were not sufficient to significantly reduce available water content over the two-year period, prolonged drainage water application could amplify these effects over time. Therefore, soil physical indicators should be systematically included in long-term monitoring strategies for sustainable irrigation management.

Chemical changes and salinity-sodicity risk

As shown by the chemical results presented above, particularly the increases in electrical conductivity (EC) under drainage water treatments, soil chemical properties responded more sensitively to irrigation with agricultural drainage water than soil physical properties. The increase in electrical conductivity under drainage water treatments reflects the cumulative input of dissolved salts through irrigation return flows. Although EC values remained below commonly accepted thresholds for severe salinity stress, the observed upward trend indicates progressive salt accumulation that may become critical over longer irrigation periods or under limited leaching conditions. Similarly, the increase in exchangeable sodium and exchangeable sodium percentage under untreated drainage water points to the onset of sodicity-related processes. These changes are particularly important in semi-arid environments, where elevated sodium levels may gradually impair soil structure, permeability, and infiltration. The comparatively lower salinity and sodicity risk observed under treated and mixed drainage water treatments suggests that even partial improvement in irrigation water quality

can play a significant role in mitigating long-term soil degradation.

Implications for GAP irrigation systems

The Southeastern Anatolia Project (GAP) is one of the largest irrigation schemes in the region, with the Atatürk Dam supplying irrigation water to extensive agricultural areas in Şanlıurfa and surrounding provinces. The intensification of irrigation under GAP has inevitably increased agricultural drainage, which is frequently reused at the farm level during periods of water scarcity. The drainage waters evaluated in this study are therefore representative of return flows commonly encountered within the GAP irrigation network.

The findings indicate that, under current management practices, short-term reuse of agricultural drainage water within GAP-supported systems may be feasible without immediate detrimental effects on soil physical properties. Nevertheless, the observed chemical changes, particularly those related to salinity and sodicity, highlight potential long-term risks if the reuse of drainage water continues without appropriate management. In semi-arid regions such as southeastern Türkiye, high evapotranspiration rates and limited natural leaching further exacerbate salt accumulation, increasing soil vulnerability to gradual degradation.

Comparison with previous studies and broader relevance

Many previous studies on drainage or wastewater reuse have primarily focused on irrigation water quality or crop responses, often overlooking soil as an integrated system. The present study contributes to the literature by providing experimental evidence on soil responses under controlled yet field-representative conditions over two years. The results align with studies reporting that chemical changes precede physical degradation in soils irrigated with marginal-quality waters, reinforcing the notion that soil chemical indicators serve as early warning signals (Rengasamy, 2010; Feizi et al., 2010).

Although the experimental duration was limited to two years, the observed trends are consistent with long-term projections from similar semi-arid environments. Therefore, the findings are not only relevant to GAP irrigation areas but also applicable to other large-scale irrigation schemes worldwide, where drainage water reuse is increasingly considered an adaptive strategy for addressing water scarcity.

CONCLUSIONS

This study evaluated the effects of 2 years of irrigation with agricultural drainage water on soil physical and chemical properties under semi-arid conditions representative of southeastern Türkiye. The results indicate that short- to medium-term reuse of agricultural drainage water did not cause severe deterioration of soil physical properties, reflecting the buffering capacity of the fine-textured alluvial soils and the relatively limited duration of the experiment.

This indicates that soil chemical parameters can serve as early indicators of potential soil degradation under drainage water irrigation, preceding observable changes in soil physical properties. Increases in soil electrical conductivity and exchangeable sodium percentage were observed in treatments receiving drainage water, particularly untreated drainage water, highlighting the potential for progressive salinity and sodicity development. Although these changes did not reach critical thresholds over the two years, they are early warning signs of long-term degradation in soil quality if the reuse of drainage water continues without appropriate management practices.

The findings are particularly relevant to large-scale irrigation systems such as the Southeastern Anatolia Project (GAP), where extensive irrigation relies on water from the Atatürk Dam. Under such conditions, the reuse of drainage water may be feasible in the short term; however, continuous monitoring of soil salinity and sodicity indicators is essential to ensure the sustainability of irrigated lands in semi-arid environments. The results emphasize that drainage water

reuse should not be evaluated solely as a water-saving practice but rather as a soil management issue with cumulative effects. Regular monitoring of soil salinity and sodicity, combined with appropriate leaching strategies and, when feasible, blending drainage water with freshwater, may help sustain soil quality under drainage-water irrigation. Without such measures, even moderate increases in soil salinity and sodium levels may compromise long-term land productivity in semi-arid irrigation systems.

Overall, this study demonstrates that the effects of drainage water reuse are more pronounced on soil chemical parameters than on physical properties during the early stages of reuse. These results emphasize the importance of soil-focused assessments when evaluating alternative water resources for irrigation and provide experimental evidence to support informed soil and water management strategies in semi-arid regions.

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