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Beyond SAR: evaluating CROSS for predicting soil structural stability under recycled water irrigation

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Abstract

The increasing use of recycled water for irrigation requires reliable indicators to assess potential impacts on soil physical properties. Traditional irrigation water quality assessments rely primarily on the Sodium Adsorption Ratio (SAR) to evaluate soil permeability hazards; however, SAR does not account for the potential dispersive effects of potassium or differences in the flocculating roles of calcium and magnesium.

This study evaluated the influence of irrigation water cation composition on soil structural stability using a greenhouse experiment with strawberry plants irrigated with synthetic recycled waters of contrasting cation ratios. Standing water occurrence, relative infiltration rate, clay dispersion and volumetric soil water content were monitored to assess soil physical responses.

Irrigation with waters dominated by dispersive cations increased drainage impairment, reduced relative infiltration and promoted clay dispersion compared with calcium-dominated treatments. Clay dispersion was strongly associated with irrigation water cation composition and appeared to be the primary mechanism driving soil structural degradation. Among the evaluated indices, the Cation Ratio of Soil Structural Stability (CROSSf) showed stronger relationships with soil physical indicators than SAR.

These results are consistent with previous laboratory column experiments and confirm that CROSSf provides improved predictions of soil permeability hazards under cropping conditions. Incorporating indices such as CROSS into irrigation water quality assessment frameworks may improve the management of agricultural systems increasingly relying on recycled water.

1. Introduction

Water is a finite resource and is becoming increasingly scarce in many regions of the world due to population growth, climate change and increasing competition among agricultural, urban and industrial sectors. Agriculture is the largest consumer of freshwater resources globally and therefore plays a central role in water resource management and food security. As freshwater availability declines, the use of alternative or non-conventional water resources has gained increasing attention as a strategy to sustain agricultural production (Drechsel et al. 2023).

Among these alternative resources, the reuse of treated wastewater for irrigation is increasingly recognized as an important component of integrated water resources management. Wastewater reuse offers opportunities to alleviate pressure on freshwater supplies while supporting agricultural production and nutrient recycling (Pescod 1992; Toze 2006; Asano et al. 2007; Pedrero et al. 2010; Levy et al. 2011; Drechsel et al. 2023).

The chemical composition of irrigation water plays a critical role in controlling soil physical and chemical processes. In particular, the relative concentrations of major cations such as sodium (Na^+), potassium (K^+), calcium (Ca^{2+}) and magnesium (Mg^{2+}) can strongly influence soil structural stability and hydraulic

conductivity. High concentrations of dispersive cations may promote clay swelling and dispersion, leading to aggregate breakdown, soil sealing and reductions in infiltration and permeability (McNeal and Coleman 1966; Frenkel et al. 1978; Shainberg et al. 1981; Shainberg and Letey 1984; Suarez et al. 2006).

Recycled irrigation water frequently differs from natural freshwater sources in terms of cation composition. While potassium concentrations in natural waters are typically low, treated wastewater often contains higher levels of potassium derived from domestic and industrial sources (Arienzo et al. 2009; Chand et al. 2020). Consequently, irrigation with recycled water may significantly alter soil cation balances and increase the risk of soil structural degradation.

Traditionally, the potential impact of irrigation water on soil structural stability has been evaluated using the Sodium Adsorption Ratio (SAR), which considers sodium as the primary dispersive cation affecting soil structure (Richards 1954). SAR has been widely used for decades in irrigation water quality guidelines and has proven useful for evaluating sodicity hazards in many irrigated systems. However, SAR assumes that sodium is the dominant dispersive ion and does not consider the potential dispersive effects of potassium. In addition, SAR assumes that calcium and magnesium exert equal flocculating effects on soil structure, which may not always reflect their actual behavior in soil systems (Qadir et al. 2021).

Recent research has demonstrated that potassium and magnesium can influence soil structural stability under irrigation with marginal-quality waters (Rengasamy and Marchuk 2011; Smith et al. 2015; Qadir et al. 2021). To address these limitations, the Cation Ratio of Soil Structural Stability (CROSS) was proposed as an alternative index that incorporates the relative dispersive and flocculating effects of Na^+, K^+, Ca^{2+} and Mg^{2+} (Rengasamy and Marchuk 2011). By accounting for the contribution of potassium and differentiating the flocculating roles of calcium and magnesium, CROSS has been suggested to provide improved predictions of soil permeability hazards compared with SAR (Smith et al. 2015; Qadir et al. 2021).

Previous laboratory column experiments have demonstrated that the cation composition of recycled irrigation water strongly influences soil structural stability and saturated hydraulic conductivity. In particular, the Cation Ratio of Soil Structural Stability (CROSSf) has been shown to outperform the traditional Sodium Adsorption Ratio (SAR) in predicting reductions in soil permeability when potassium is present in irrigation water (Aldughaishi et al. 2024).

While these laboratory findings provide valuable mechanistic insights into the role of cation composition in soil structural degradation, their applicability under cropping conditions remains insufficiently explored. Soil–water interactions under cultivated conditions may differ from laboratory systems due to factors such as plant root activity, soil structure heterogeneity and irrigation management practices.

Therefore, further experimental evidence under conditions closer to agricultural production systems is required to evaluate the practical implications of these findings.

To address this gap, the present study investigated the interaction between monovalent cations (Na^+ and K^+) and divalent cations (Ca^{2+} and Mg^{2+}) on soil infiltration rate, volumetric soil water content, permeability and soil structural stability. Synthetic recycled irrigation waters of varying quality were prepared using chloride salts to generate solutions with similar salinity but contrasting cation ratios. These synthetic waters were then applied to soils cultivated with strawberry plants under controlled greenhouse conditions.

2. Materials and methods

2.1 Experimental setup

This study evaluated the effects of irrigation water cation composition on soil physical properties under controlled greenhouse conditions. The experimental design builds upon previous laboratory column experiments that investigated the effects of recycled water cation composition on soil structural stability and saturated hydraulic conductivity (Aldughaishi et al. 2024).

The term CROSSf used in this study refers to the modified application of the original CROSS concept proposed by Rengasamy and Marchuk (2011), adapted to evaluate the specific contribution of irrigation water cation composition to soil permeability responses under recycled water irrigation conditions. The notation CROSSf was adopted to distinguish the formulation used in this study from the original CROSS index while maintaining the same theoretical basis regarding the balance between dispersive and flocculating cations

The previous laboratory study demonstrated that the cation composition of irrigation water strongly influences soil permeability and clay dispersion and showed that the Cation Ratio of Soil Structural Stability (CROSSf) provided improved prediction of soil permeability reductions compared with the traditional Sodium Adsorption Ratio (SAR) when potassium was present in irrigation water (Aldughaishi et al. 2024).

While those laboratory experiments provided important mechanistic insights into soil structural responses to different cation compositions, the extent to which these effects occur under cropping conditions remains uncertain. Therefore, the present study was designed to evaluate these interactions under conditions closer to agricultural production systems using potted soil cultivated with strawberry plants in a greenhouse.

The experiment was conducted under controlled greenhouse conditions at the University of California, Davis. Strawberry plants were grown in pots filled with an air-dried clay loam soil characterized by a bulk density of 1.3 g cm^{-3}, a cation exchange capacity (CEC) of 21.1 meq 100 g^{-1}, and an initial exchangeable sodium percentage (ESP) of 0.6%.

Prior to transplanting, each pot received 45 g of a slow-release fertilizer (15N–9P–12K) to ensure adequate nutrient supply throughout the growing season. Pots were arranged following a randomized

complete block design with four replications per treatment.

2.2 Soil collection and preparation

Soil was collected from an agricultural research field site located at the University of California Davis, near Davis CA (38º 32’ N,121º 45 W). The soil was taken from the top 0 to 30 cm soil depth after removing the small layer at the top (5 to 10 cm) that could potentially contain a high level of organic matter. Table 1 lists some of the physical and chemical properties of the collected soil.

Table 1
Physical and chemical properties of the soil used in the experiment and the methods of determination.

Parameter (unit)	**Average value (standard deviation)**	**Method**
EC_e (dS/m)	0.95 (± 0.06)	Saturated paste extract
pH	7.1 (± 0.53)	Saturated paste extract
sand (%)	35.06 (± 0.86)	Hydrometer
silt (%)	31.56 (± 1.73)	Hydrometer
clay (%)	33.38% (± 1.25)	Hydrometer
gravel (%)	0.06% (± 0.06)	Gravimetric (scale)
texture	clay loam	USDA classification
field BD (g/cm^3)	1.33 (± 0.09)	Core sample
organic carbon	1.26 (± 0.08)	Loss-on-ignition
Exchangeable Na (meq/100g)	0.13 (± 0.01)	ICP-AES
Exchangeable K (meq/100g)	0.83 (± 0.07)	ICP-AES
Exchangeable Ca (meq/100g)	8.27 (± 0.25)	ICP-AES
Exchangeable Mg (meq/100g)	11.83 (± 0.32)	ICP-AES
CEC (meq/100g)	21.1 (± 0.53)	Measured
ESP (%)	0.60 (± 0.53)	Measured
dominant clay mineral	Montmorillonite	From literature[1]

[1] From Dasberg and Hopmans (1992)

Pots were filled with the air-dried soil that was screened through a 6 mm sieve to provide a reasonable starting point for soil structure similar to field conditions. Three successive layers were packed carefully to achieve an average bulk density of 1.3 g/cm^3 which was similar to that measured in the field. The top

of each layer was shattered to minimize layer-to-layer stratification. The total water content was accounted for by measuring the moisture content of the air-dried soil which was 59.5 mg-water/g-soil (± 5.0, n = 15).

2.3 2.3 Preparation of synthetic irrigation waters and greenhouse experiment

To evaluate the influence of cation composition on soil structural stability, synthetic irrigation waters were prepared using chloride salts. The solutions were designed to simulate recycled irrigation water with similar salinity levels but contrasting cation compositions. Synthetic waters were prepared using combinations of the following salts: sodium chloride (NaCl), potassium chloride (KCl), calcium chloride ($CaCl_2$), magnesium chloride ($MgCl_2$).

The solutions were formulated to maintain similar electrical conductivity while varying the ratios of monovalent cations (Na^+ and K^+) and divalent cations (Ca^{2+} and Mg^{2+}). This approach allowed the effects of cation composition to be evaluated independently of total salinity. For each solution, Sodium Adsorption Ratio (SAR) and Cation Ratio of Soil Structural Stability (CROSSf) values were calculated following the formulations proposed by Richards (1954) and Rengasamy and Marchuk (2011), respectively.

A total of 176 pots were prepared with four replicates per treatment and four pots per replication. The experiment followed a randomized complete block design with four blocks and 11 treatments.

The treatments were designed to mimic synthetic recycled water with specific cationic content to evaluate the parameters used to predict infiltration and soil structure degradation. All treatments had an electrical conductivity of 1.5 dS/m using chloride solutions of sodium, potassium, calcium and/or magnesium except for one treatment made of calcium sulfate (Table 2) which was used to evaluate the effect of chloride on the plants. The treatments were designed to have SAR values of 0, 4.9, 9.8 and infinity (sodium chloride solution). The same treatments had CROSSf and CROSSopt values ranging from 0 to 12.6 and from 0 to 35.6, respectively.

Table 2
Synthetic treated recycled water chemical composition for various treatments.

Treatments	T0	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10
EC (dS/m)	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
NaCl (mmol/L)	0	15	12	12	12	6	6	6	0	0	0
KCl (mmol/L)	0	0	0	0	0	6	6	6	12	12	12
$CaCl_2$ (mmol/L)	0	0	1.5	0.75	0	1.5	0.75	0	1.5	0.75	0
$MgCl_2$ (mmol/L)	0	0	0	0.75	1.5	0	0.75	1.5	0	0.75	1.5
$CaSO_4$ (mmol/L)	20	0	0	0	0	0	0	0	0	0	0
SAR	0	∞	9.80	9.80	9.80	4.90	4.90	4.90	0	0	0
$CROSS_f$	0	∞	9.80	10.95	12.65	7.64	8.54	9.87	5.49	6.13	7.08
$CROSS_{opt}$	0	∞	9.80	13.36	35.59	6.54	8.92	23.75	3.28	4.48	11.92

The treatments were applied to the soil in the pots using spaghetti drip irrigation which was based on two criteria: leaching factor of 30% to maintain the soil EC below the threshold ECe of strawberry plants and a tensiometer reading below 10% (Fig. 1). The soil in the pots was irrigated every day throughout the 40-week growing period. From the start of the irrigation (week 1) to week 22, the irrigation was provided in 50 ml pulses every 15 mins. After week 22, the irrigation was provided in 100 ml pulses every 15 mins. The irrigation was provided between the hours of 11:00 AM to 1:15 PM. The occurrence of standing water in the pots prior to subsequent irrigation events was used as an indirect indicator of relative soil drainage behavior and permeability limitations. Although this approach does not provide direct measurements of saturated hydraulic conductivity, it allows comparative assessment of treatment effects on soil structural degradation under repeated irrigation conditions.

2.4 Soil physical measurements

Soil drainage response evaluation

The impact of synthetic recycled water irrigation on soil structure was evaluated by counting the number of pots with standing-water approach, as an indicator of relative soil drainage and permeability behavior under repeated irrigation conditions. The occurrence of standing water in the pots prior to subsequent irrigation events was used as an indirect indicator of relative soil drainage behavior and permeability limitations. Although this approach does not provide direct quantitative measurements of saturated

hydraulic conductivity, it allows comparative assessment of soil structural degradation among treatments under repeated irrigation conditions. Two permeability tests were performed. The first test was conducted every two weeks during the growing period from week 26 to week 38 by counting the number of pots with standing water about an hour before the next irrigation event. The second test was performed at the end of the experiment over a period of 39 hours, starting from time 0 (exactly when irrigation stopped). The measurements were taken while the plants were still in the pots and with varying frequencies: 0, 0.5, 1, 1.5, 2, 3, 6, 15, 27, and 39 hours. The results were reported as the percentage of pots with standing water.

Relative infiltration response

To evaluate treatment effects on relative infiltration, infiltration tests were conducted on three randomly selected pots from each of the 11 treatments at the end of the greenhouse experiments after removing the shoots of the plants (the roots were not removed from the soil). The infiltrometer measurements were intended primarily for comparative evaluation among treatments rather than for determining absolute field-scale hydraulic conductivity values. The Wooding infiltrometer was used and a total of 33 infiltration tests were conducted. Infiltration rates were then correlated with SAR, CROSSf, and CROSSopt. The results of the Wooding infiltrometer were reported as relative infiltration rates normalized to treatment T0 because the actual saturated hydraulic conductivity could not be measured for several reasons. First, the size of the pots was larger than the size of the infiltrometer base, so a soil ring was used above the soil in the pots. Second, it was required to measure the moisture content before running the infiltration test and after the infiltration test. The latter could be performed easily, however, the former was not possible without damaging the soil and causing channels through the pots. Third, the pots were not wide enough to ensure consistent lateral water movement like would be the case in the field. Lastly, the pots had a larger top diameter than the bottom. Therefore, each infiltration test was run for about an hour for each replication, and the last few datapoints (around 8) were used to estimate the infiltration rate from the slope of the line of the cumulative infiltrated water depth over time. The measured infiltration rate of treatment 0 was used as a reference point to the other treatments.

Soil moisture evaluation

Volumetric soil water content was measured 4 and 7 days after the end of the experiment (after removing the plants). Volumetric soil water content was measured using a TDR315 soil moisture sensor (Acclima Inc, Meridian Idaho). The 4-day measurement was found to be insignificant among the treatments, and therefore only the analysis of the 7-day moisture content was considered. Thirteen measurements per treatment were collected from all pots except those used for the infiltration experiment; values were aggregated at the replicate level for statistical comparisons.

Soil structure evaluation by clay dispersion

Samples were collected from the pots 5 to 10 cm and 10 to 15 cm depth with four replicates from each treatment (a total of 88 samples) using a soil auger sampler. The top layer of soil (0 to 5 cm) was

excluded from the analysis due to high fertilizer levels. The estimation of dispersed clay followed the method of spontaneous dispersion developed by Marchuk et al. (2013). For this analysis, 40 g of an oven-dried sample collected from the pots were placed in 250 ml graduated cylinder, and 200 ml of deionized water was added. The mixture was left for 5 hours, and then the soil was stirred into suspensions and left to stand for 2 hours. To estimate the dispersed clay, 10 ml of the solution was pipetted from a depth of 10 cm, and the solution was oven-dried to obtain the weight (mg) using a sensitive scale with an accuracy of ± 0.1 mg.

Models for predicting soil permeability hazard

The common soil infiltration assessment based on irrigation water quality is the Sodium Adsorption Ratio (SAR) (Richards 1954):

SAR = Na+ / sqrt[(Ca2 + + Mg2+)/2] (1)

where Na^{+}, Ca^{2+} and Mg^{2+} are the concentrations of the ions in mmol/L. Regarding monovalent and divalent cation weight on clay dispersion or flocculation, Rengasamy and Marchuk (2011) developed the Cation Ratio of Soil Structural Stability (CROSS):

CROSSf = (Na + + 0.56 K+) / sqrt(Ca2 + + 0.60 Mg2+) (2)

where K^{+} is the concentration of the potassium ion in mmol/L. The subscript *f* indicates that the factors of K and Mg "are based on the relative flocculating power". Smith et al. (2015) further optimized Eq. 2 to provide best-fit factors less than one for K and Mg using threshold electrolyte concentration (TEC) experimental data from Arienzo et al. (2012). The result was:

CROSSopt = (Na + + 0.335 K+) / sqrt(Ca2 + + 0.0758 Mg2+) (3)

where the subscript *opt* indicates optimization.

2.5 Statistical analysis

Statistical analyses were performed to evaluate treatment effects on standing water occurrence, relative infiltration rate, dispersed clay, and volumetric soil water content. Treatment effects were tested using one-way analysis of variance (ANOVA). When significant treatment effects were detected ($p < 0.05$), means were separated using Tukey's honestly significant difference test. Linear regression analyses were conducted to evaluate relationships between soil physical indicators and irrigation water cation indices (SAR, CROSSf and CROSSopt). Treatment T1 was excluded from regression analyses involving cation ratios because SAR, CROSSf and CROSSopt were infinite due to the absence of divalent cations. Results are reported as means ± standard error.

3. Results

3.1 Soil drainage during the critical cropping period

Soil drainage responses to irrigation water cation composition were evaluated by monitoring the presence of standing water in the pots during the cropping period. The presence of standing water prior to the next irrigation event was interpreted as an indicator of reduced infiltration and impaired soil drainage.

The mean percentage of pots exhibiting standing water during the critical cropping period differed significantly among treatments (Fig. 2; ANOVA, $p < 0.001$). The sodium-dominated treatment (T1) showed the highest occurrence of standing water, whereas the calcium-dominated treatment (T0) exhibited the lowest values. Intermediate treatments showed distinct responses depending on their cation composition, with treatments containing higher proportions of dispersive cations generally showing greater standing water occurrence.

The temporal evolution of standing water occurrence during weeks 26–38 is provided in Online Resource 1.

3.2 Soil drainage after irrigation termination

To further evaluate the effect of irrigation water cation composition on soil drainage capacity, a drainage test was conducted at the end of the experiment by terminating irrigation and monitoring the occurrence of standing water over a 39-h period. Because treatment differences were most clearly expressed within the first hours after irrigation ceased, the percentage of pots with standing water at 6 h was selected as a representative indicator of drainage impairment.

Standing water occurrence at 6 h differed significantly among treatments (Fig. 3; ANOVA, $p < 0.001$). The calcium-dominated treatment (T0) showed the lowest standing water occurrence, with only 18.3% of pots showing standing water. In contrast, treatments characterized by higher proportions of dispersive cations showed markedly greater ponding. The highest values were observed in T7, T4 and T1, which exhibited standing water in more than 88% of pots.

Treatments containing potassium but no sodium (T8, T9 and T10) showed higher standing water occurrence than T0, despite having SAR = 0. This indicates that drainage impairment was not exclusively associated with sodium enrichment. Treatments within the same SAR group also differed in their drainage behavior, suggesting that the relative proportions of K^+, Ca^{2+} and Mg^{2+} influenced soil permeability responses.

The temporal evolution of standing water occurrence during the full 39-h drainage period is provided in Online Resource 2.

3.3 CROSSf as an integrative predictor of soil physical responses

The relationships between CROSSf and the main soil physical indicators are summarized in Fig. 4. Standing water occurrence at 6 h increased with increasing CROSSf (Fig. 4A), indicating that drainage impairment became more pronounced as the relative proportion of dispersive cations increased. CROSSf explained a substantial proportion of the variability in standing water occurrence.

Relative infiltration rate decreased with increasing CROSSf (Fig. 4B), showing that irrigation water cation composition also affected the ability of water to enter the soil. Although the infiltration measurements were interpreted as relative indicators rather than absolute saturated hydraulic conductivity values, the relationship with CROSSf confirmed a consistent hydraulic response across treatments.

Dispersed clay increased strongly with increasing CROSSf (Fig. 4C). This was the strongest relationship among the evaluated soil physical indicators, indicating that clay dispersion was closely associated with the balance between dispersive and flocculating cations in the irrigation water.

Treatment T1 was excluded from the regression analyses because SAR, CROSSf and CROSSopt were infinite due to the absence of divalent cations. The comparative coefficients of determination for SAR, CROSSf and CROSSopt at different drainage times are summarized in Table 3

Table 3
Coefficients of determination (R^2) for the relationships between standing water occurrence and irrigation water cation indices at different times during the 39-h drainage experiment. Treatment T1 was excluded from regression analyses because SAR, CROSSf and CROSSopt were infinite.

Time (hr)	SAR	$CROSS_f$	$CROSS_{opt}$
0.5	0.31	0.78	0.29
1	0.30	0.77	0.31
1.5	0.37	0.73	0.21
2	0.41	0.67	0.24
3	0.49	0.86	0.40
6	0.62	0.84	0.59
15	0.48	0.59	0.59
27	0.36	0.40	0.46
39	0.37	0.32	0.41

The comparative coefficients of determination obtained for SAR, CROSSf and CROSSopt during the drainage experiment are shown in Table 3. CROSSf consistently showed stronger relationships with

standing water occurrence than SAR and CROSSopt during the early drainage period, particularly between 3 and 6 h after irrigation termination.

To provide an integrated comparison across soil physical indicators, the relationships between the measured responses and the evaluated cation indices are summarized in Table 4. CROSSf provided the strongest relationships with standing water occurrence, relative infiltration rate and dispersed clay, and also showed the strongest relationship with volumetric soil water content. Standing water occurrence, dispersed clay and volumetric soil water content increased with increasing CROSSf, whereas relative infiltration rate decreased as CROSSf increased.

Table 4
Coefficients of determination (R^2) for the relationships between soil physical indicators and irrigation water cation indices. The strongest relationship for each indicator is shown in bold in the manuscript table.

Soil physical indicator	SAR	CROSSf	CROSSopt	Best index	Direction
Standing water at 6 h	0.62	**0.84**	0.59	CROSSf	Positive
Relative infiltration rate	0.20	**0.73**	0.40	CROSSf	Negative
Dispersed clay	0.63	**0.93**	0.55	CROSSf	Positive
Volumetric soil water content	0.44	**0.81**	0.31	CROSSf	Positive

3.4 Relative infiltration response

Relative infiltration rates differed significantly among irrigation water treatments (ANOVA, $p < 0.001$). The calcium-dominated treatment (T0) exhibited the highest relative infiltration rate, whereas treatments characterized by higher proportions of dispersive cations generally showed lower infiltration values. The lowest values were observed in T4 and T7, while several intermediate treatments showed moderate reductions in infiltration relative to T0.

The negative relationship between relative infiltration rate and CROSSf (Fig. 4B) supports the use of CROSSf as an indicator of soil hydraulic impairment under irrigation with waters of contrasting cation composition. The results should be interpreted as comparative treatment responses rather than absolute estimates of saturated hydraulic conductivity.

The infiltration measurements should therefore be interpreted as relative indicators of treatment effects rather than absolute estimates of saturated hydraulic conductivity.

3.5 Clay dispersion and soil structural degradation

Clay dispersion differed significantly among treatments (Fig. 5; ANOVA, $p < 0.001$). The sodium-dominated treatment (T1) exhibited the highest dispersed clay values, whereas the calcium-dominated treatment (T0) showed the lowest values. Intermediate treatments exhibited progressively greater clay dispersion as the relative proportion of dispersive cations increased.

The strong positive relationship between dispersed clay and CROSSf (Fig. 4C) indicates that CROSSf effectively captured the cation-related processes underlying soil structural degradation. These results suggest that clay dispersion was a key mechanism contributing to the observed reductions in drainage and relative infiltration.

3.6 Volumetric soil water content after irrigation termination

Volumetric soil water content was measured several days after irrigation termination to evaluate whether treatment-induced differences in drainage were reflected in post-irrigation soil water status. Measurements conducted four days after irrigation cessation did not show statistically significant differences among treatments; therefore, only measurements obtained seven days after irrigation termination were considered for further analysis.

Volumetric soil water content varied among treatments after seven days of drainage (Fig. 6). Treatments with greater drainage impairment generally exhibited higher volumetric soil water content, whereas the calcium-dominated treatment showed lower values. These results indicate that irrigation water cation composition influenced not only surface ponding and infiltration, but also post-irrigation water redistribution within the soil profile.

4. Discussion

4.1 Irrigation water cation composition and drainage impairment

The results of this study demonstrate that irrigation water cation composition strongly influenced soil drainage behavior under greenhouse cropping conditions. Treatments dominated by calcium maintained lower standing water occurrence during both the cropping period and the drainage test after irrigation termination, whereas treatments containing higher proportions of dispersive cations showed greater ponding and reduced drainage capacity.

The sodium-dominated treatment showed the most severe drainage impairment, which is consistent with the well-established role of Na + in promoting clay swelling, aggregate breakdown, pore clogging and reduced soil permeability (Richards 1954; Quirk and Schofield 1955; McNeal and Coleman 1966; Frenkel et al. 1978; Shainberg et al. 1981; Shainberg and Letey 1984). These processes are particularly relevant in fine-textured soils, where dispersed clay particles can block conducting pores and reduce water movement through the soil profile.

Importantly, the drainage response was not only associated with sodium enrichment. Treatments containing potassium but no sodium showed higher standing water occurrence than the calcium-dominated reference treatment, despite having SAR = 0. This indicates that permeability-related risks

may occur even when SAR suggests a low sodicity hazard. Similar concerns have been reported for marginal-quality and recycled irrigation waters, where elevated K+ concentrations may contribute to soil structural degradation (Arienzo et al. 2009; Smith et al. 2015; Pedrero et al. 2010; Drechsel et al. 2023).

Overall, these results confirm that the relative balance among Na+, K+, Ca2 + and Mg2+, rather than sodium alone, controlled the observed drainage impairment. This supports the need to use irrigation water quality indicators capable of accounting for the combined effects of monovalent and divalent cations on soil structural stability.

4.2 Role of potassium and limitations of SAR

An important finding of this study is that potassium-containing treatments affected soil drainage behavior even when SAR values were low or equal to zero. This was particularly evident in treatments T8, T9 and T10, which contained no sodium but showed higher standing water occurrence than the calcium-dominated reference treatment. This response indicates that potassium can contribute to soil structural degradation under specific irrigation water compositions and that permeability-related risks cannot always be attributed exclusively to sodium.

Although sodium is generally considered the dominant dispersive cation in irrigation water quality assessments, potassium may also promote clay dispersion when present at elevated concentrations. The dispersive effect of K + is usually weaker than that of Na+, but it can still influence soil aggregate stability, especially in fine-textured soils and under repeated irrigation with waters containing appreciable K+ concentrations (Lagerwerff and Brower 1972; Arienzo et al. 2009; Smith et al. 2015; Chand et al. 2020). This is particularly relevant for recycled irrigation water, which may contain higher potassium concentrations than conventional freshwater sources due to domestic and industrial inputs (Pedrero et al. 2010; Drechsel et al. 2023).

The traditional SAR index does not account for the potential dispersive contribution of potassium and assumes that calcium and magnesium have equivalent flocculating effects. These assumptions may be adequate for many conventional irrigation waters, but they are less suitable for waters with complex cation composition, such as treated wastewater or blended non-conventional water resources (Smith et al. 2015; Qadir et al. 2021). Recent work has therefore highlighted the need to reconsider SAR-based approaches when evaluating soil structural stability under irrigation with recycled or marginal-quality waters (Qadir et al. 2021; WRF 2023).

The results of the present study support this concern. Treatments with similar SAR values showed contrasting drainage and infiltration responses, indicating that SAR alone did not fully capture the influence of cation composition on soil physical behavior. This provides a strong justification for using indices such as CROSS, which include the relative effects of Na+, K+, Ca2 + and Mg2 + on soil structural stability.

4.3 CROSSf as an integrative predictor of soil physical responses

The results of this study show that CROSSf provided a consistent relationship with several independent soil physical responses, including standing water occurrence, relative infiltration rate and clay dispersion. This consistency is important because these variables represent different but connected aspects of soil structural degradation: surface drainage impairment, water entry into the soil and clay particle mobilization.

The synthesis presented in Fig. 4 shows that standing water occurrence and dispersed clay increased with increasing CROSSf, whereas relative infiltration rate decreased as CROSSf increased. These opposite but coherent response directions indicate that higher CROSSf values were associated with greater soil structural instability, reduced pore continuity and impaired hydraulic functioning. The summary of predictive performance across soil physical indicators further supports this interpretation, as CROSSf was the best-performing index for the evaluated responses (Table 4).

The stronger performance of CROSSf compared with SAR can be attributed to its ability to incorporate the relative effects of Na+, K+, Ca2 + and Mg2 + on soil structural stability. Whereas SAR only accounts for sodium relative to calcium and magnesium, CROSSf explicitly includes the contribution of potassium and differentiates the flocculating effects of calcium and magnesium. This makes CROSSf more suitable for evaluating irrigation waters with complex cation composition, including recycled waters (Rengasamy and Marchuk 2011; Smith et al. 2015; Qadir et al. 2021).

These findings are consistent with previous laboratory column experiments, in which CROSSf outperformed SAR in predicting reductions in saturated hydraulic conductivity under irrigation with waters of contrasting cation composition (Aldughaishi et al. 2024). The present greenhouse study extends those findings by demonstrating that CROSSf also explains soil physical responses under cropping conditions, where repeated irrigation, root activity and soil heterogeneity may influence the development of structural degradation.

Overall, the results support the use of CROSSf as an integrative indicator of soil structural risk under recycled water irrigation. Rather than replacing detailed soil physical measurements, CROSSf may provide a practical screening tool to identify irrigation waters with higher potential to induce drainage impairment, reduced infiltration and clay dispersion.

4.4 Clay dispersion as the mechanism controlling permeability decline

Clay dispersion appeared to be the main mechanism linking irrigation water cation composition with the observed reductions in drainage and relative infiltration. The strong treatment effect on dispersed clay, together with the close relationship between dispersed clay and CROSSf, indicates that the balance between dispersive and flocculating cations directly affected soil structural stability.

The calcium-dominated treatment showed the lowest dispersed clay values, confirming the stabilizing role of Ca2 + in promoting clay flocculation and aggregate stability. In contrast, treatments dominated by

sodium or characterized by high CROSSf values exhibited greater clay dispersion, indicating the breakdown of soil aggregates and the mobilization of fine particles. Once dispersed, clay particles can migrate through the soil matrix and accumulate in conducting pores, reducing pore continuity, limiting water entry and slowing drainage. This mechanism is consistent with classical descriptions of permeability decline in sodic soils and with previous studies on clay dispersion under irrigation with marginal-quality waters (Quirk and Schofield 1955; Suarez et al. 2006; Marchuk et al. 2013).

The relationship between clay dispersion and the hydraulic indicators measured in this study provides a coherent explanation for the observed soil physical responses. Higher clay dispersion was associated with greater standing water occurrence and lower relative infiltration rates, indicating that structural degradation affected both surface drainage and water entry into the soil. The higher volumetric soil water content observed in some treatments after irrigation termination may also reflect reduced macroporosity and slower gravitational drainage caused by pore blockage.

These results reinforce the idea that irrigation water quality affects soil hydraulic functioning through physicochemical effects on soil structure. In this context, CROSSf performed well because it represents the combined influence of Na + and K + as dispersive cations and Ca2 + and Mg2 + as stabilizing cations. Therefore, the strong clay dispersion response provides mechanistic support for the use of CROSSf as a predictor of soil structural degradation under recycled water irrigation.

4.5 Implications for recycled water irrigation management and study limitations

The increasing use of recycled water in agriculture requires irrigation water quality indicators that reflect the full cation composition of the water, not only sodium hazard. Recycled waters may contain relevant concentrations of K+, Mg2 + and other dissolved constituents that differ from those commonly found in conventional freshwater sources. Therefore, relying exclusively on SAR may lead to an incomplete assessment of soil structural risks, particularly in fine-textured soils or in systems subjected to long-term irrigation with non-conventional water resources (Asano et al. 2007; Pedrero et al. 2010; Muyen et al. 2011; Levy et al. 2011; Drechsel et al. 2023).

The results of this study suggest that CROSSf could be used as a complementary indicator to SAR for evaluating soil permeability hazards under recycled water irrigation. CROSSf may help identify irrigation waters with a higher potential to induce clay dispersion, drainage impairment and reduced infiltration before severe structural degradation becomes evident in the field. This is particularly relevant for irrigation management decisions involving water blending, amendment application, leaching management or the long-term monitoring of soil physical quality.

From a practical perspective, the use of CROSSf could improve risk assessment frameworks by accounting for the combined effects of Na+, K+, Ca2 + and Mg2+. This approach is consistent with recent recommendations highlighting the need to reconsider SAR-based approaches when evaluating soil structural stability under waters with complex cation composition (Qadir et al. 2021; WRF 2023).

However, CROSSf should not be interpreted as a standalone replacement for field monitoring. Rather, it should be used together with soil texture, salinity, electrolyte concentration, irrigation frequency, drainage conditions and crop sensitivity.

This study was conducted under controlled greenhouse conditions using synthetic recycled waters with similar salinity but contrasting cation ratios. This experimental approach allowed the specific effect of cation composition to be isolated, but it also limits direct extrapolation to field conditions where soil heterogeneity, rainfall, evaporation, root development and management practices may modify soil structural responses. In addition, soil solution chemistry was not monitored throughout the experiment, and therefore the relationships reported here are based on irrigation water composition rather than direct measurements of evolving soil solution SAR or CROSS.

Future studies should evaluate CROSSf under field conditions, include temporal monitoring of soil solution chemistry and assess its performance across contrasting soil textures, salinity levels and irrigation management strategies. Such studies would help determine threshold values for practical irrigation water quality guidelines and support the broader incorporation of CROSS-type indices into recycled water management frameworks.

5. Conclusions

This study evaluated the effect of irrigation water cation composition on soil structural stability and hydraulic functioning under greenhouse cropping conditions using synthetic recycled waters with similar salinity but contrasting cation ratios.

Irrigation water composition significantly affected soil physical behavior. Waters enriched in dispersive cations increased standing water occurrence during the cropping period and after irrigation termination, reduced relative infiltration rate and promoted clay dispersion compared with the calcium-dominated reference treatment.

Clay dispersion appeared to be the main mechanism explaining the observed drainage and infiltration impairment. Treatments with higher dispersed clay also showed poorer drainage behavior and lower relative infiltration, indicating that cation-induced structural degradation affected both surface ponding and water entry into the soil.

Among the evaluated cation indices, CROSSf consistently provided the strongest relationships with the measured soil physical responses, including standing water occurrence, relative infiltration rate and clay dispersion. In contrast, SAR did not fully capture the effects of potassium or the differential roles of calcium and magnesium on soil structural stability.

These findings are consistent with previous laboratory column experiments and extend their relevance to cropping conditions. The results indicate that SAR-based irrigation water quality assessments may

underestimate soil structural risks when recycled water contains relevant concentrations of potassium or variable divalent cation composition.

Overall, CROSSf may provide a useful complementary indicator for assessing soil permeability hazards under recycled water irrigation. Its incorporation into irrigation water quality evaluation frameworks could improve the identification of structural risks and support more robust management of agricultural systems increasingly relying on non-conventional water resources.

Declarations

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Competing interests: The authors declare no competing interests.

Ethics approval: This study did not involve human participants or animals.

Data availability: Data are available from the corresponding author upon reasonable request.

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Figures

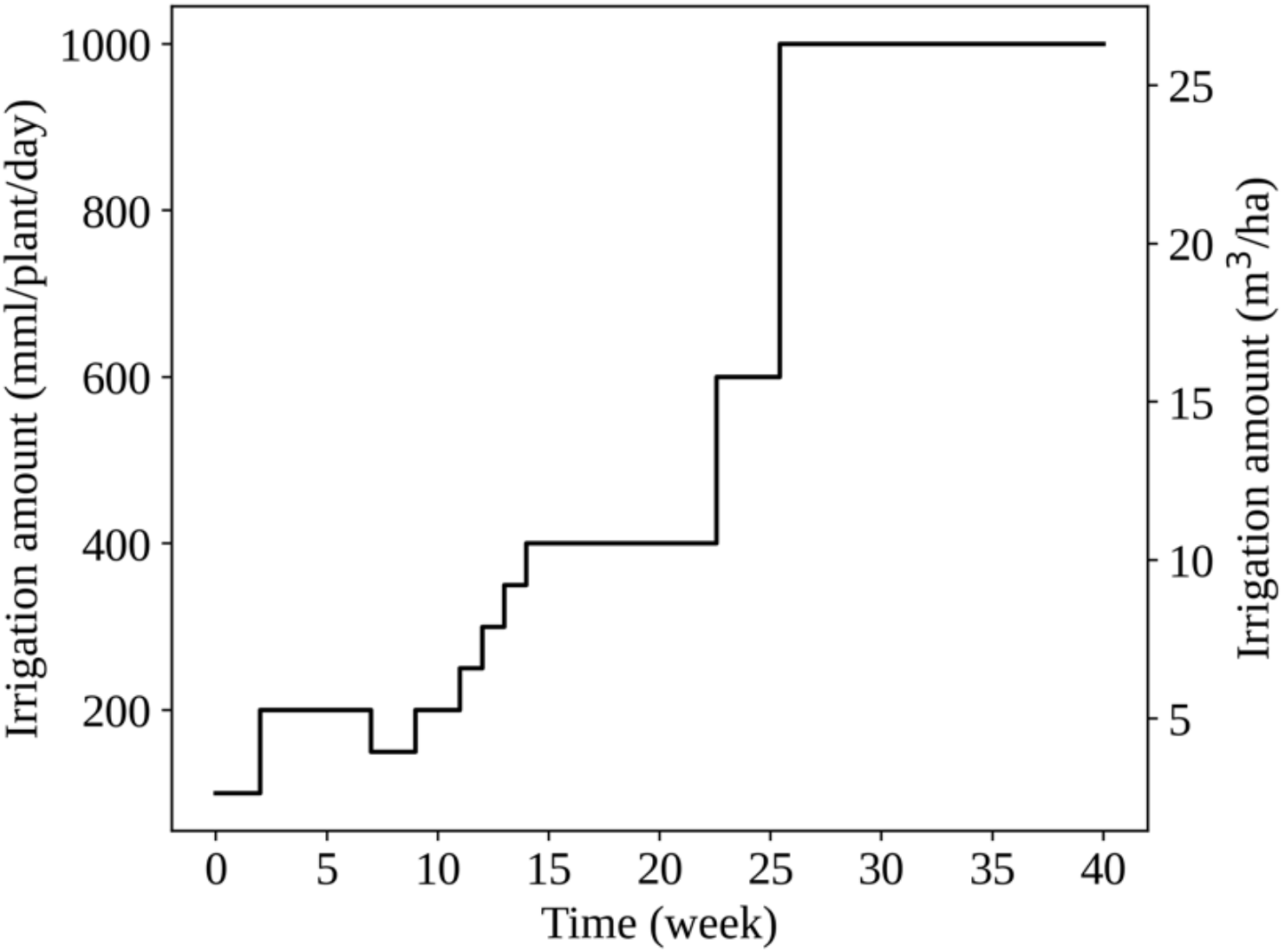


Figure 1

Irrigation scheduling during the greenhouse experiment based on leaching fraction and tensiometer readings. Irrigation was managed to maintain adequate soil moisture while minimizing salt accumulation in the root zone.

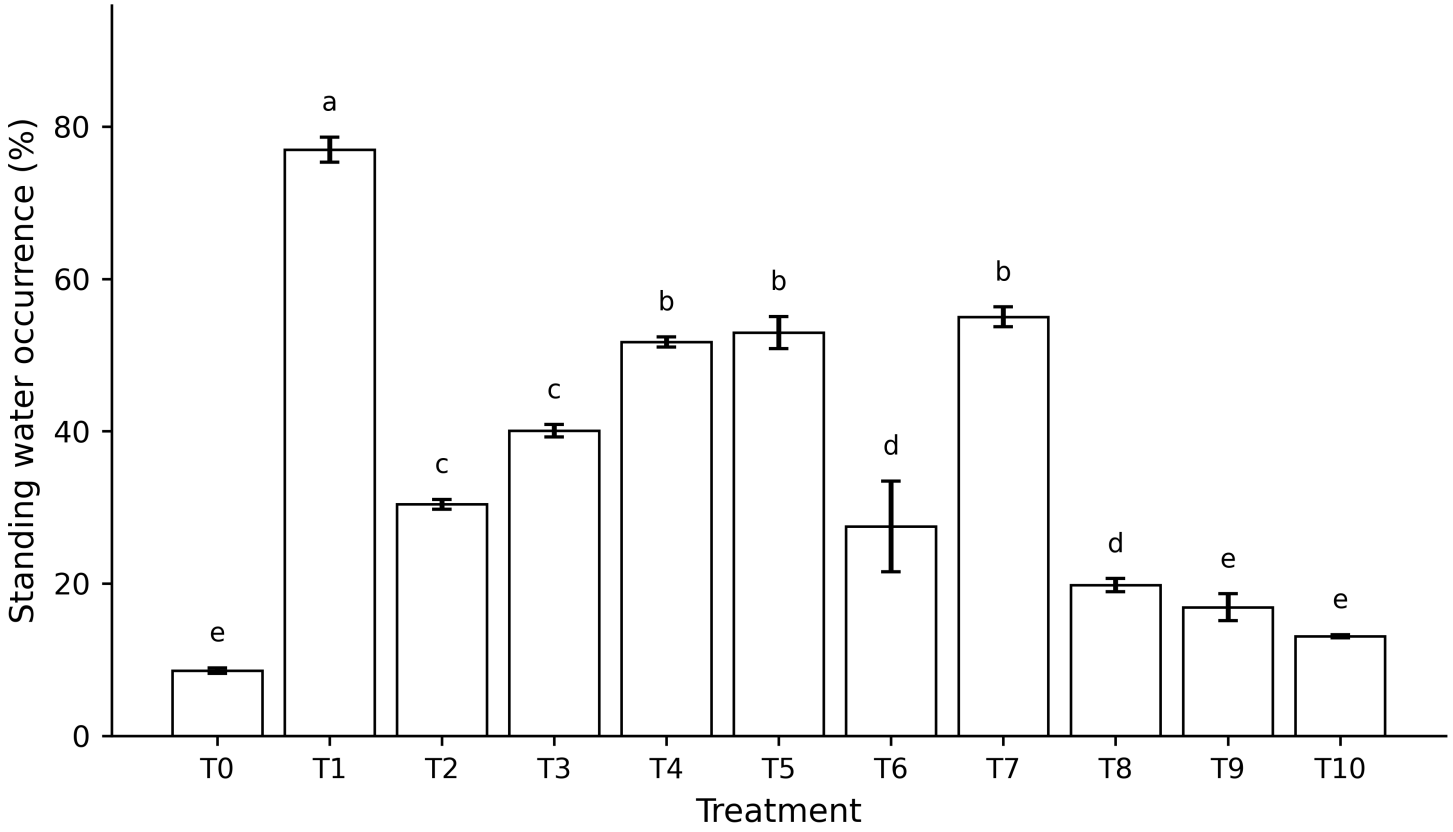


Figure 2

Mean percentage of pots exhibiting standing water during the critical cropping period (weeks 26–38) as affected by irrigation water cation composition. Bars represent treatment means ± standard error (n = 4). Different letters indicate significant differences among treatments according to Tukey's HSD test ($p < 0.05$).

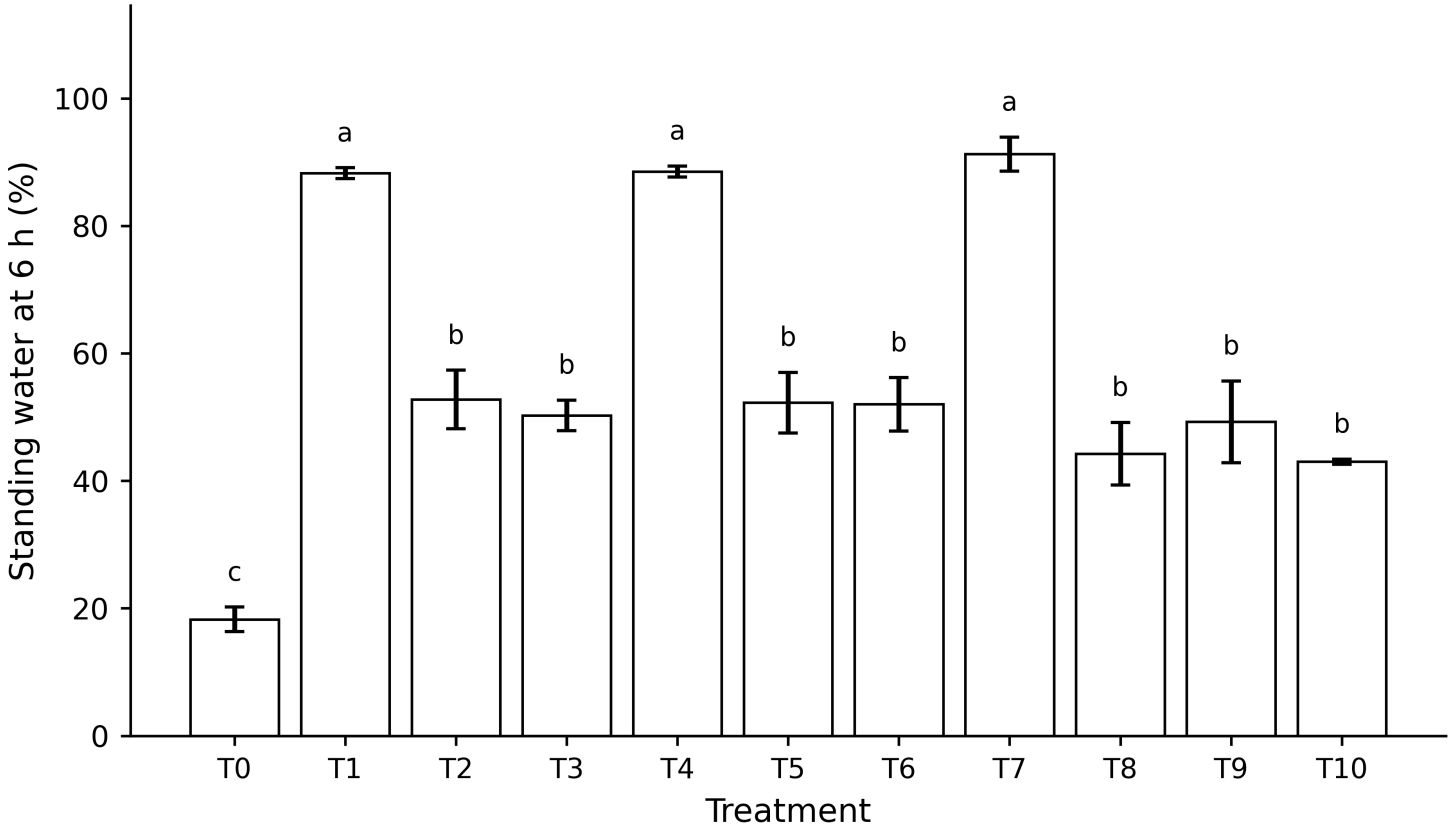


Figure 3

Mean percentage of pots exhibiting standing water 6 h after irrigation termination. Bars represent treatment means ± standard error (n = 4). Different letters indicate significant differences among treatments according to Tukey's HSD test ($p < 0.05$).

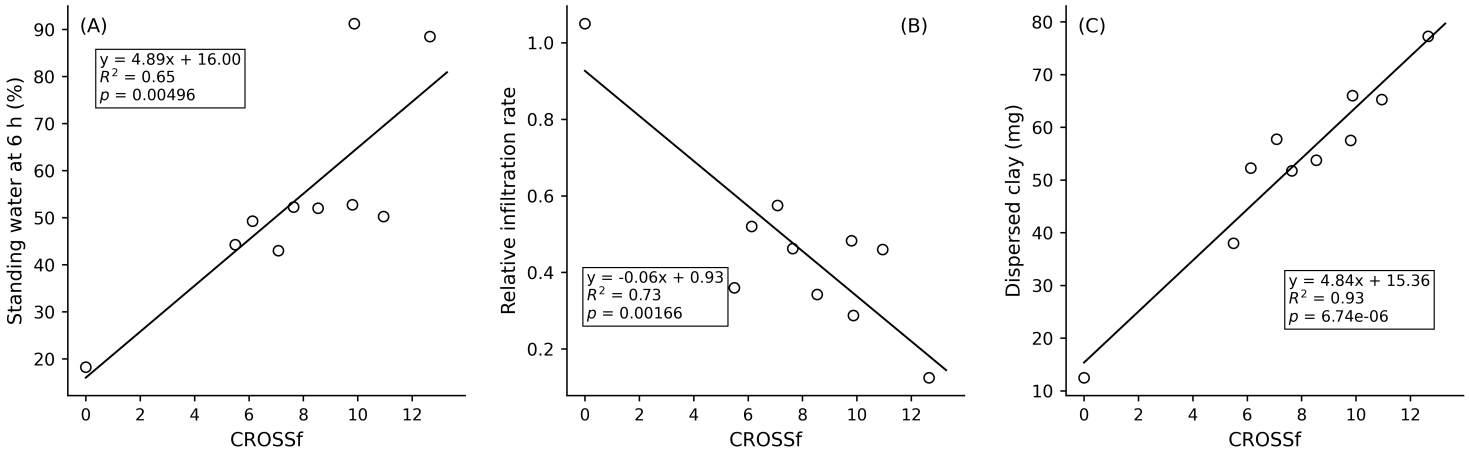


Figure 4

Summary of the relationships between CROSSf and soil physical indicators. (A) Relationship between standing water occurrence 6 h after irrigation termination and CROSSf. (B) Relationship between relative infiltration rate and CROSSf. (C) Relationship between dispersed clay and CROSSf. Regression lines and

coefficients of determination (R^2) are shown. Treatment T1 was excluded from the regressions because CROSSf was infinite.

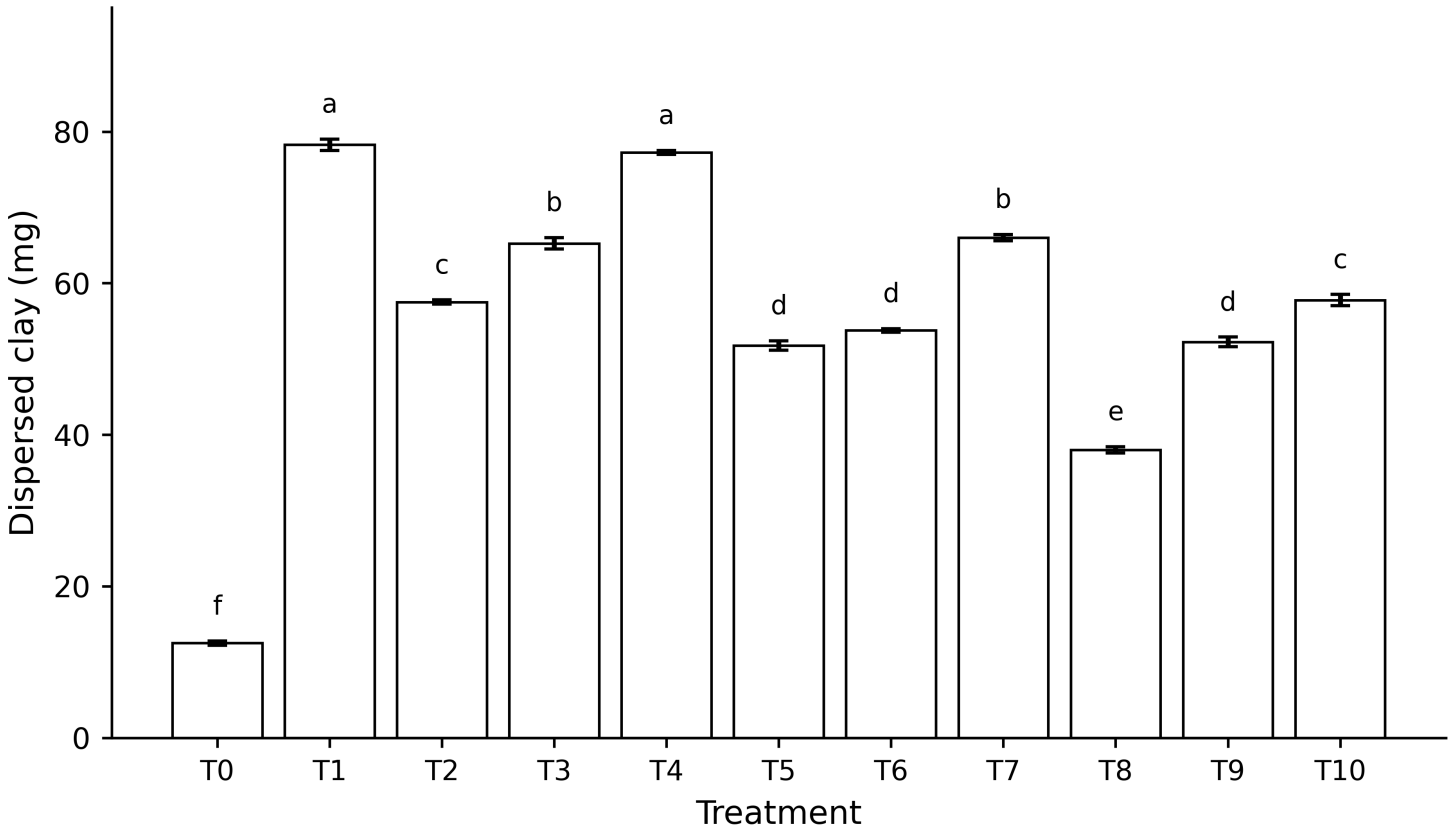


Figure 5

Effect of irrigation water cation composition on soil clay dispersion. Dispersed clay was measured in soil samples collected at the end of the experiment. Bars represent treatment means ± standard error (n = 4). Different letters indicate significant differences among treatments according to Tukey's HSD test ($p < 0.05$).

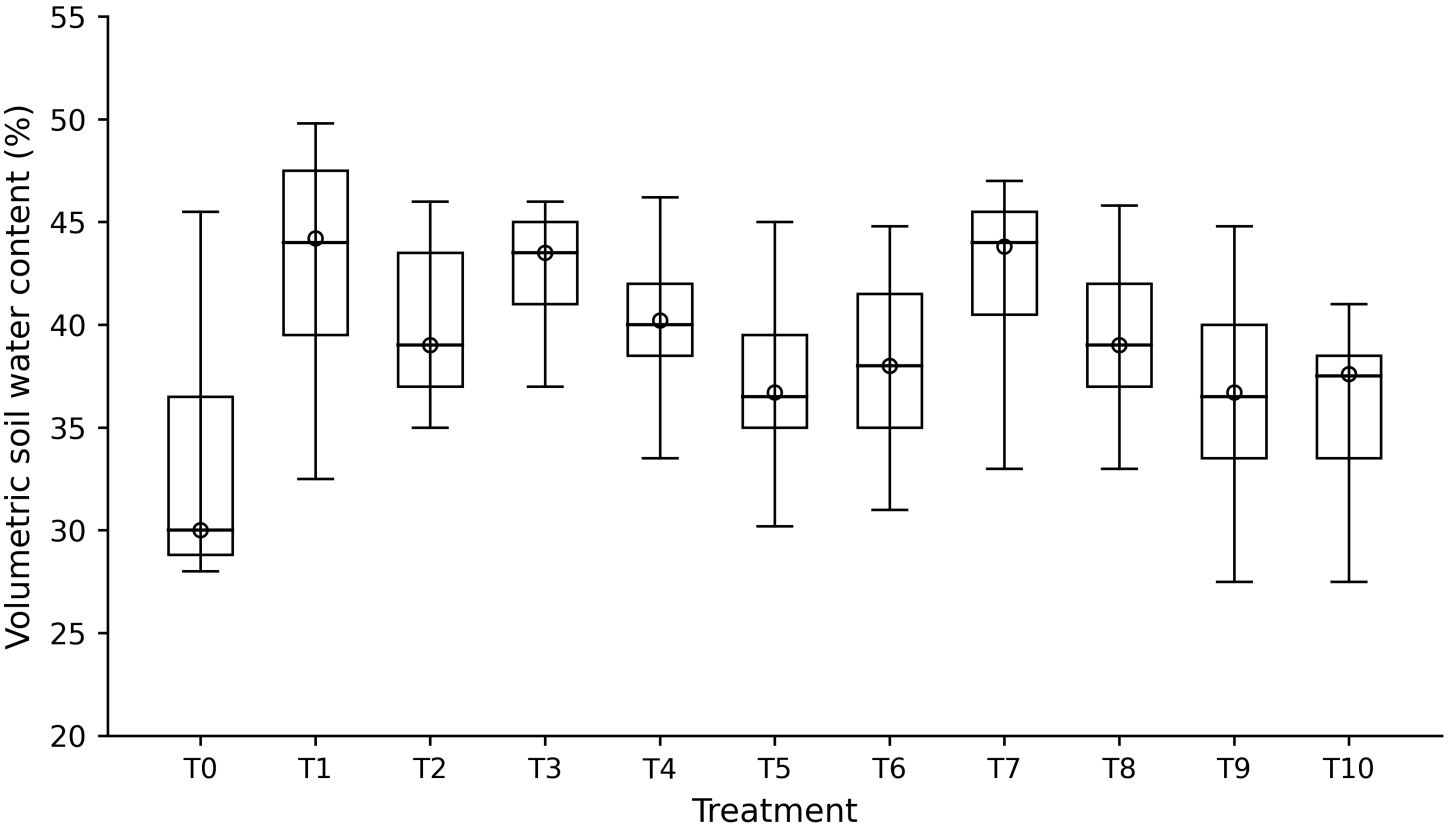


Figure 6

Volumetric soil water content measured seven days after irrigation termination in pots irrigated with synthetic recycled waters of contrasting cation composition. Boxes indicate the interquartile range, horizontal lines indicate medians, whiskers indicate the observed range, and open circles indicate treatment means.

Supplementary Files

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