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Research Article

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Multi-cation irrigation water composition affects strawberry growth, yield, and fruit quality beyond SAR-based sodicity assessment

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Abstract

Aims: Recycled and marginal-quality waters are increasingly used in irrigated horticulture, but their cation composition may affect crop performance beyond the effects of total salinity. Strawberry (Fragaria × ananassa) is a high-value, salt-sensitive crop that requires favorable root-zone conditions to sustain canopy development, fruit yield and marketable quality. This study evaluated strawberry growth, yield, fruit soluble solids and tissue ion accumulation under irrigation with synthetic waters of constant salinity but contrasting Na, K, Ca and Mg composition.

Methods: Eleven treatments were designed to generate contrasting sodium adsorption ratio (SAR), Cation Ratio of Soil Structural Stability based on flocculating coefficients (CROSSf), and optimized CROSS (CROSSopt) values, including treatments with similar SAR but different cation balances. Plants were grown for 40 weeks under greenhouse conditions, and root-zone response, canopy cover, biomass, fruit yield, fruit soluble solids concentration and shoot ion accumulation were measured.

Results: Irrigation water cation composition strongly affected strawberry performance. The calcium-dominated control maintained the highest canopy cover, biomass and yield, whereas the sodium-dominated extreme treatment produced the lowest crop performance and the highest fruit soluble solids concentration, indicating a yield-quality trade-off under severe stress. Treatments with similar SAR values differed in canopy development, yield and tissue ion accumulation, showing that crop response was controlled by broader cation composition rather than sodium alone. CROSSf explained more variability than SAR for key crop-response variables, including late-season canopy cover, marketable yield and biomass.

Conclusions: These results indicate that multi-cation irrigation water composition can influence strawberry productivity and fruit quality under recycled or marginal-quality irrigation. Incorporating indices such as CROSSf may improve interpretation of crop responses and management decisions in high-value horticultural systems.

Keywords: strawberry; fruit quality; recycled water irrigation; cation composition; sodicity; soluble solids; CROSS; SAR

Introduction

Strawberry (Fragaria × ananassa) is a high-value horticultural crop whose productivity and fruit quality are strongly influenced by root-zone salinity, aeration and nutrient balance. Because strawberry has a relatively shallow root system and is sensitive to both osmotic and ionic stress, maintaining favorable root-zone conditions is essential for sustaining canopy development, marketable yield and fruit quality (Barroso and Alvarez 1997; Keutgen and Pawelzik 2009; Ferreira et al. 2019).

At the same time, water scarcity is driving the increasing use of non-conventional water resources, including recycled and marginal-quality waters, in irrigated agriculture (Pescod 1992; Toze 2006; FAO 2021; Drechsel et al. 2023). Recycled water can provide a reliable supply and opportunities for nutrient recycling, but its chemical composition often differs from that of conventional freshwater, particularly in the relative concentrations of Na, K, Ca and Mg (Pedrero et al. 2010; Arienzo et al. 2009; Chand et al. 2020). These differences may affect both root-zone physical conditions and plant ion balance, with potential consequences for high-value horticultural crops.

Irrigation water sodicity is traditionally evaluated using the sodium adsorption ratio (SAR), which considers sodium as the primary dispersive cation affecting soil structure (Richards 1954). However, SAR does not account for the potential

contribution of potassium or for differences in the stabilizing roles of calcium and magnesium. To address these limitations, the Cation Ratio of Soil Structural Stability (CROSS) was proposed as a multi-cation index incorporating the combined effects of Na, K, Ca and Mg on soil structural stability (Rengasamy and Marchuk 2011). Subsequent studies have shown that CROSS can improve predictions of soil permeability and clay dispersion compared with SAR, particularly under waters containing relevant concentrations of K and Mg (Arienzo et al. 2012; Smith et al. 2015; Qadir et al. 2021).

Although the mechanistic basis of SAR and CROSS is rooted in soil physical processes, the agronomic relevance of these indices depends on whether differences in irrigation water cation composition translate into measurable crop responses. Previous laboratory column experiments showed that cation composition can strongly influence soil structural stability and hydraulic conductivity, with CROSSf providing improved prediction of permeability reductions compared with SAR when potassium is present in irrigation water (Aldughaishi et al. 2024). However, crop-level responses under controlled production conditions, including yield and fruit quality, remain insufficiently quantified.

For strawberry production, this knowledge gap is particularly relevant because reductions in drainage, aeration or nutrient balance may affect both vegetative growth and reproductive performance. Poor soil physical conditions can limit root function and plant productivity (Armstrong and Drew 2002; Henderson and Patrick 2018; Singh et al. 2018), while salinity and ionic stress can alter fruit size, yield and soluble solids concentration (Keutgen and Pawelzik 2009; Galli et al. 2016; Ferreira et al. 2019). Few studies have isolated the role of irrigation water cation composition at constant salinity and evaluated its combined effects on strawberry growth, productivity, fruit quality and tissue ion accumulation.

Therefore, the objective of this study was to evaluate the effects of irrigation water cation composition on strawberry canopy development, yield, fruit quality, biomass and tissue ion accumulation under controlled greenhouse conditions, and to compare the predictive performance of SAR, CROSSf and CROSSopt for these crop-level responses. We hypothesized that irrigation waters with higher effective sodicity would reduce strawberry growth and marketable productivity, and that CROSSf would provide a better predictor of crop response than SAR because it accounts for potassium and the differential roles of calcium and magnesium.

Materials and methods

Soil and pot setup

Soil was collected from the upper 30 cm of an agricultural field at the University of California, Davis, after removing the upper 5-10 cm organic-enriched layer. The soil was classified as clay loam, with 35% sand, 32% silt and 33% clay. Saturated paste electrical conductivity (EC) and pH were 0.95 ± 0.06 dS m-1 and 7.1 ± 0.5, respectively. Organic carbon was 1.26 ± 0.08%, and field bulk density was 1.3 ± 0.1 g cm-3. The dominant clay mineral was montmorillonite. Exchangeable Na, K, Ca and Mg were 0.13 ± 0.01, 0.83 ± 0.07, 8.27 ± 0.25 and 11.83 ± 0.32 meq 100 g-1, respectively, resulting in a cation exchange capacity (CEC) of 21.1 meq 100 g-1 and an exchangeable sodium percentage (ESP) of 0.6%.

A total of 176 plastic pots, approximately 20 cm in diameter and 25 cm deep, with drainage holes, were filled with air-dried soil sieved through a 6-mm mesh. Soil was packed in three increments, with each layer lightly scarified before adding the next, to reduce artificial layering and achieve an average bulk density of 1.3 g cm-3. One bare-root strawberry transplant (*Fragaria × ananassa* Duch., cv. Portola) was planted in each pot. To provide non-limiting nutrition, 45 g of slow-release fertilizer (15-9-12 NPK Osmocote, 8-9-month release) was incorporated into the upper soil layer of each pot. Pots were arranged in a randomized complete block design with four blocks and 11 irrigation treatments, with four pots per treatment in each block. The greenhouse experiment lasted 40 weeks.

Irrigation water treatments

The irrigation treatments (Table 1) were designed to isolate the effects of irrigation water cation composition on crop response while maintaining constant salinity. Synthetic waters were prepared using combinations of Na, K, Ca and Mg to generate contrasting SAR, Cation Ratio of Soil Structural Stability based on flocculating coefficients (CROSSf), and optimized CROSS (CROSSopt) values. For interpretation and graphical presentation, treatments were grouped according to their experimental purpose and dominant cation composition: calcium-dominated control (T0), sodium-dominated extreme (T1), SAR 9.8 group

(T2-T4), SAR 4.9 group (T5-T7) and potassium-dominated SAR = 0 group (T8-T10). These groups were used consistently in the figures to facilitate comparison among waters with similar SAR but different cation composition.

All treatment solutions had an EC of 1.5 dS m-1. The target SAR values were 0, 4.9, 9.8 and infinity. CROSSf values ranged from 0 to 12.65, with one extreme treatment having infinite CROSS values. The chemical composition of all treatments is summarized in Table 1.

SAR and CROSS indices were calculated from irrigation water cation concentrations expressed in mmol L-1. SAR was calculated as Na / sqrt[(Ca + Mg)/2] (Richards 1954). CROSSf was calculated as (Na + 0.56K) / sqrt(Ca + 0.60Mg), where the K and Mg coefficients represent the relative dispersive and flocculating effects used in the original CROSS formulation (Rengasamy and Marchuk 2011). CROSSopt was calculated as (Na + 0.335K) / sqrt(Ca + 0.0758Mg), following the optimized coefficients proposed by Smith et al. (2015).

Table 1. Composition of synthetic irrigation waters used to isolate the effects of cation balance on strawberry response at constant salinity. All solutions had an electrical conductivity of 1.5 dS m-1. Ion concentrations are expressed in mmol L-1. Treatments are grouped according to dominant cation composition and experimental comparison.

Treatment group	Treatment	Experimental purpose	Na	K	Ca	Mg	SAR	CROSSf	CROSSopt
Ca-dominated control	T0	Reference treatment representing structurally stable irrigation water	0	0	20	0	0	0	0
Na-dominated extreme	T1	Maximum sodicity scenario	15	0	0	0	∞	∞	∞
SAR 9.8 group	T2	High SAR; Ca-dominated	12	0	8	0	9.8	9.8	9.8
SAR 9.8 group	T3	High SAR; mixed Ca/Mg	12	0	4	4	9.8	10.95	13.36
SAR 9.8 group	T4	High SAR; Mg-dominated	12	0	0	8	9.8	12.65	35.59
SAR 4.9 group	T5	Intermediate SAR; Ca-dominated	6	6	8	0	4.9	7.64	6.54
SAR 4.9 group	T6	Intermediate SAR; mixed Ca/Mg	6	6	4	4	4.9	8.54	8.92
SAR 4.9 group	T7	Intermediate SAR; Mg-dominated	6	6	0	8	4.9	9.87	23.75
K-dominated (SAR=0)	T8	Potassium effect without sodium; Ca-dominated	0	12	8	0	0	5.49	3.28
K-dominated (SAR=0)	T9	Potassium effect without sodium; mixed Ca/Mg	0	12	4	4	0	6.13	4.48
K-dominated (SAR=0)	T10	Potassium effect without sodium; Mg-dominated	0	12	0	8	0	7.08	11.92

Irrigation management and root-zone monitoring

All pots were irrigated daily using drip irrigation to maintain a target leaching fraction of approximately 30%. This leaching regime was intended to limit excessive salt accumulation in the root zone while maintaining comparable irrigation management across treatments. Representative pots were monitored using tensiometers, and irrigation frequency was adjusted to maintain soil water tension above -10 cbar.

During the first 22 weeks, irrigation was applied in 50 mL pulses every 15 min between 11:00 and 13:15 each day. From week 22 until the end of the experiment, the pulse volume was increased to 100 mL to maintain leaching as plant water demand increased. The irrigation schedule is shown in Supplementary Fig. S2.

Late-season leachate EC was measured from drainage samples to assess whether irrigation water cation composition generated treatment-dependent differences in root-zone solution chemistry. Together with volumetric water content and ponding persistence, these measurements were used to evaluate root-zone responses to contrasting irrigation water composition.

Plant growth, yield and fruit quality measurements

Plant growth and production were monitored using repeated non-destructive measurements and final harvest variables. Every two weeks, starting at week 2, overhead digital images of each pot were taken under consistent lighting and camera height to estimate green canopy cover. Images were processed using the Foliage/Canopeo approach (Patrignani and Ochsner 2015), and canopy cover was calculated as the percentage of pot area covered by green vegetation.

Runners were removed as they emerged to minimize resource diversion, and weeds were removed manually. Ripe strawberries were harvested weekly from week 6 to week 40. Fruits were counted, weighed fresh and classified as marketable when they weighed >10 g and had no major shape or color defects. Fruits not meeting these criteria were classified as nonmarketable. Fruit sugar content was measured as soluble solids concentration (°Brix) using a handheld refractometer on representative berries collected during the fruiting period.

At the end of the experiment, aboveground plant biomass was harvested by cutting plants at the soil surface. Fresh biomass was recorded, and samples were oven-dried at 60 °C to constant weight to determine dry biomass. Roots were not recovered because of the difficulty of separating them from the soil matrix.

Plant tissue analysis

Dried shoot tissues from the final harvest were ground for ion analysis. For each treatment and block, dried plant material was composited and subsampled. Cations were extracted by microwave digestion using HNO3/H2O2 and analyzed by inductively coupled plasma atomic emission spectroscopy (ICP-AES) to determine Na, K, Ca and Mg concentrations. Chloride was extracted from a separate subsample with deionized water and measured by ion chromatography. Ion concentrations were expressed on a dry weight basis.

Statistical analysis

Statistical analyses were performed to evaluate treatment effects on canopy cover, yield, biomass, fruit quality and tissue ion concentrations. Treatment effects were assessed 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 (HSD) test. Late-season canopy cover was analyzed using average values from weeks 30-40, corresponding to the period when treatment differences were most pronounced.

Relationships between irrigation water quality indices and crop response variables were evaluated using linear regression. The coefficients of determination (R2) were calculated for SAR, CROSSf and CROSSopt against selected response variables, including late-season canopy cover, total yield, marketable yield, fresh biomass and dry biomass. The sodium-dominated extreme treatment (T1), with infinite SAR and CROSS values, was excluded from linear regression analyses involving cation indices. All analyses were conducted at a significance level of $p < 0.05$.

Results

Root-zone conditions under contrasting irrigation water composition

Root-zone conditions differed among irrigation treatment groups, indicating that irrigation water cation composition modified the physical and chemical environment experienced by strawberry plants (Fig. 1). Volumetric water content was lowest in the calcium-dominated control and increased in treatments with greater sodic or dispersive cation influence (Fig. 1A). The sodium-dominated extreme treatment showed the highest root-zone water retention, suggesting reduced drainage and lower air-filled porosity.

Ponding persistence followed a similar pattern (Fig. 1B). The sodium-dominated treatment maintained standing water for longer periods than the calcium-dominated control and the intermediate treatment groups, indicating impaired water movement through the root zone under highly sodic conditions. The potassium-dominated SAR = 0 group showed intermediate behavior, suggesting that potassium-rich waters may also influence soil hydraulic behavior despite having no sodium hazard according to SAR.

Late-season leachate EC differed among treatment groups (Fig. 1C), showing that irrigation water composition also influenced root-zone solution chemistry during the experiment. Overall, these results confirm that the treatments generated contrasting root-zone environments, providing a mechanistic basis for interpreting plant growth and yield responses.

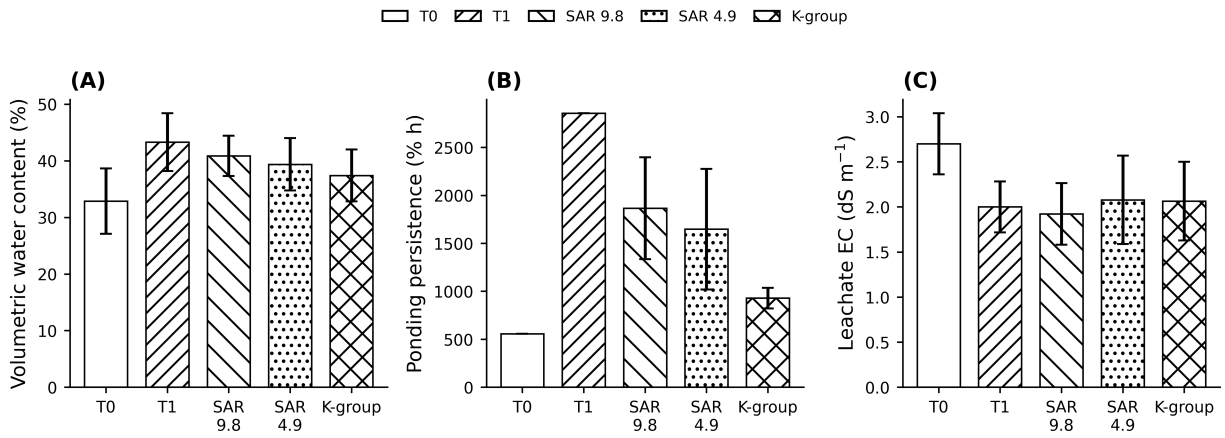


Fig. 1. Root-zone context for strawberry plants irrigated with waters of contrasting cation composition. Panels show (A) volumetric water content, (B) ponding persistence and (C) late-season leachate electrical conductivity (EC). Treatments are grouped as calcium-dominated control (T0), sodium-dominated extreme (T1), SAR 9.8 group (T2-T4), SAR 4.9 group (T5-T7) and potassium-dominated SAR = 0 group (T8-T10). Error bars indicate SD.

Canopy development and crop vigor

Strawberry canopy cover increased during the early stages of the experiment, with relatively small differences among treatments during the initial growth period (Fig. 2). However, treatment differences became progressively more evident as the experiment advanced, especially after week 25.

During the late-season period, weeks 30-40, significant differences in average canopy cover were observed among treatments (Table 2). The calcium-dominated control, T0, maintained the highest canopy cover, whereas the sodium-dominated extreme treatment, T1, showed the lowest canopy development. This late-season divergence indicates that the effects of irrigation water cation composition accumulated over time rather than producing only an immediate growth response.

Table 2. Late-season canopy cover of strawberry plants irrigated with waters of contrasting cation composition. Values are means ± SD for weeks 30-40. Treatments sharing at least one letter are not significantly different according to Tukey's HSD test ($p < 0.05$).

Treatment group	Treatment	SAR	CROSSf	CROSSopt	Canopy cover (%)	n	Tukey group
Calcium-dominated control	T0	0	0	0	57.6 ± 27.7	128	A
SAR 4.9 group	T5	4.9	7.64	6.54	49.8 ± 29.7	128	B
K-dominated (SAR=0)	T10	0	7.08	11.92	46.3 ± 34.5	128	BC
K-dominated (SAR=0)	T9	0	6.13	4.48	45.2 ± 33.1	128	BC
K-dominated (SAR=0)	T8	0	5.49	3.28	44.4 ± 31.3	128	BCD
SAR 9.8 group	T2	9.8	9.8	9.8	42.4 ± 31.0	128	CD
SAR 4.9 group	T6	4.9	8.54	8.92	41.8 ± 33.9	128	CD
SAR 9.8 group	T4	9.8	12.65	35.59	38.8 ± 28.8	128	D
SAR 4.9 group	T7	4.9	9.87	23.75	31.3 ± 30.2	128	E
SAR 9.8 group	T3	9.8	10.95	13.36	30.0 ± 28.6	128	E
Sodium-dominated extreme	T1	∞	∞	∞	16.8 ± 22.4	128	F

Differences were also observed among treatments with similar SAR values. Potassium-dominated treatments with SAR = 0 did not perform equivalently to the calcium-dominated control, despite having the same SAR value. Likewise, within the SAR 4.9 and SAR 9.8 groups, canopy cover varied depending on Ca/Mg balance and CROSSf values. These results indicate that canopy development was influenced by the broader cation composition of irrigation water, not only by sodium as represented by SAR.

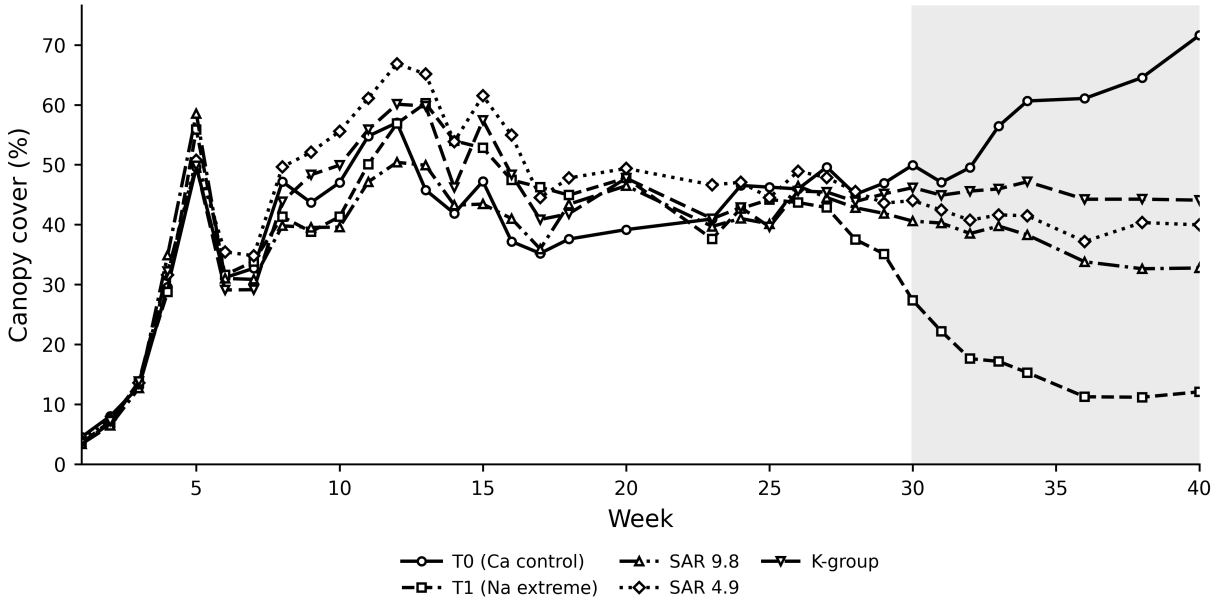


Fig. 2. Temporal evolution of strawberry canopy cover under irrigation waters with contrasting cation composition. Treatments are grouped as calcium-dominated control (T0), sodium-dominated extreme (T1), SAR 9.8 group (T2–T4), SAR 4.9 group (T5–T7) and potassium-dominated SAR = 0 group (T8–T10). The shaded region marks the late-season period (weeks 30–40) used for statistical comparisons in Table 2.

Fruit yield and marketable productivity

Fruit production varied among irrigation treatments and reflected the cumulative effects observed in canopy development and root-zone response (Fig. 3). The calcium-dominated control maintained the highest productivity, whereas the sodium-dominated extreme treatment showed the lowest fruit yield. Intermediate responses were observed in the SAR 4.9, SAR 9.8 and potassium-dominated groups.

The late-season yield response was particularly relevant because it coincided with the period when canopy differences among treatments were greatest. Treatments with reduced canopy development also tended to show lower fruit productivity, suggesting that cumulative root-zone stress affected both vegetative growth and reproductive performance.

Marketable yield was also affected by irrigation water composition (Fig. 3B). The reduction in marketable production under more stressful treatments indicates that cation composition influenced not only total fruit biomass but also commercial productivity. These results highlight the agronomic importance of considering multi-cation water quality effects when using recycled or marginal-quality irrigation water.

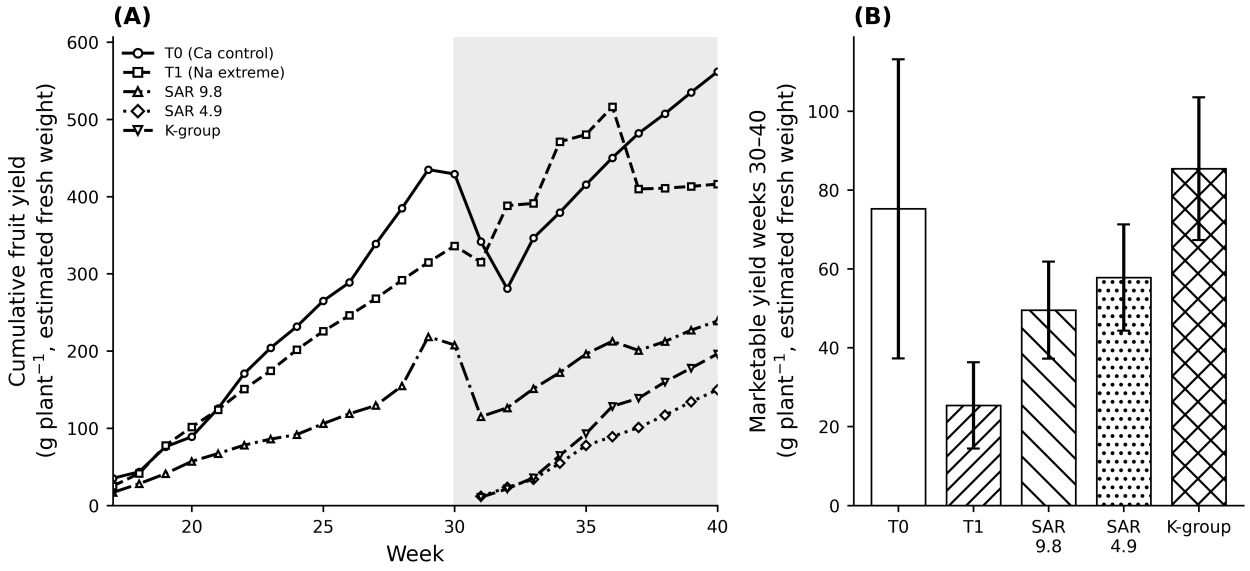


Fig. 3. Strawberry fruit productivity under irrigation waters with contrasting cation composition. Panels show (A) cumulative fruit yield and (B) late-season marketable yield (weeks 30-40) for grouped irrigation treatments. Treatments are grouped as calcium-dominated control (T0), sodium-dominated extreme (T1), SAR 9.8 group (T2-T4), SAR 4.9 group (T5-T7) and potassium-dominated SAR = 0 group (T8-T10). Yield is expressed as estimated fresh weight based on the observed fresh-dry fruit weight relationship. Error bars in panel B indicate SE.

Predictive value of SAR and CROSS for crop response

Regression analyses showed that CROSSf provided a more consistent predictor of strawberry response than SAR across several agronomic variables (Fig. 4). CROSSf explained a greater proportion of variability than SAR for late-season canopy cover, marketable yield and fresh biomass. This supports the hypothesis that an index incorporating Na, K, Ca and Mg provides a better representation of crop response than an index based mainly on sodium relative to calcium and magnesium.

The improved performance of CROSSf was particularly relevant for comparisons among treatments with similar SAR values. In the SAR = 0 treatments, the potassium-dominated waters generated different canopy and productivity responses from the calcium-dominated control, despite having identical SAR. Similarly, within the SAR 4.9 and SAR 9.8 groups, crop performance varied according to Ca/Mg balance and CROSSf. These internal comparisons demonstrate that SAR alone did not fully capture the effect of irrigation water chemistry on strawberry response.

CROSSopt did not consistently outperform CROSSf, suggesting that the standard CROSSf formulation may be more appropriate for explaining crop-level responses under the conditions of this experiment. Overall, these results support the use of CROSSf as a more informative index for evaluating irrigation water quality effects on strawberry growth and productivity.

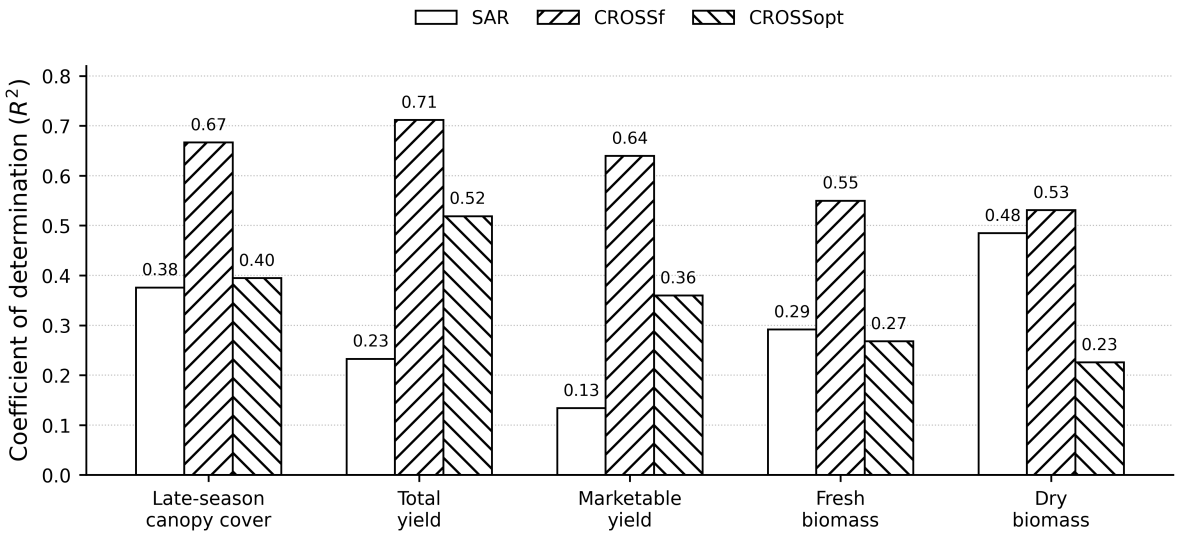


Fig. 4. Predictive value of SAR, CROSSf and CROSSopt for strawberry crop-response variables. Bars show coefficients of determination (R2) from linear regressions between each irrigation water quality index and selected crop responses, including late-season canopy cover, total yield, marketable yield, fresh biomass and dry biomass. The sodium-dominated extreme treatment (T1) was excluded because SAR and CROSS values were infinite.

Yield-quality trade-off in fruit production

Fruit sugar content, expressed as soluble solids concentration, varied among irrigation treatments and showed a contrasting pattern relative to yield (Fig. 5). The sodium-dominated extreme treatment produced the lowest yield but the highest °Brix, indicating a clear yield-quality trade-off under severe sodic stress.

The calcium-dominated control maintained higher productivity but lower fruit sugar concentration, whereas intermediate treatments occupied positions between these two extremes. This pattern suggests that increasing stress associated with irrigation water cation composition reduced productivity while increasing soluble solids concentration in fruit.

This response is agronomically relevant because higher °Brix should not be interpreted as improved overall crop performance when it occurs together with substantial yield reductions. In this experiment, increased fruit sugar concentration was associated with reduced canopy development, biomass and fruit production, indicating a stress-related response rather than enhanced crop function.

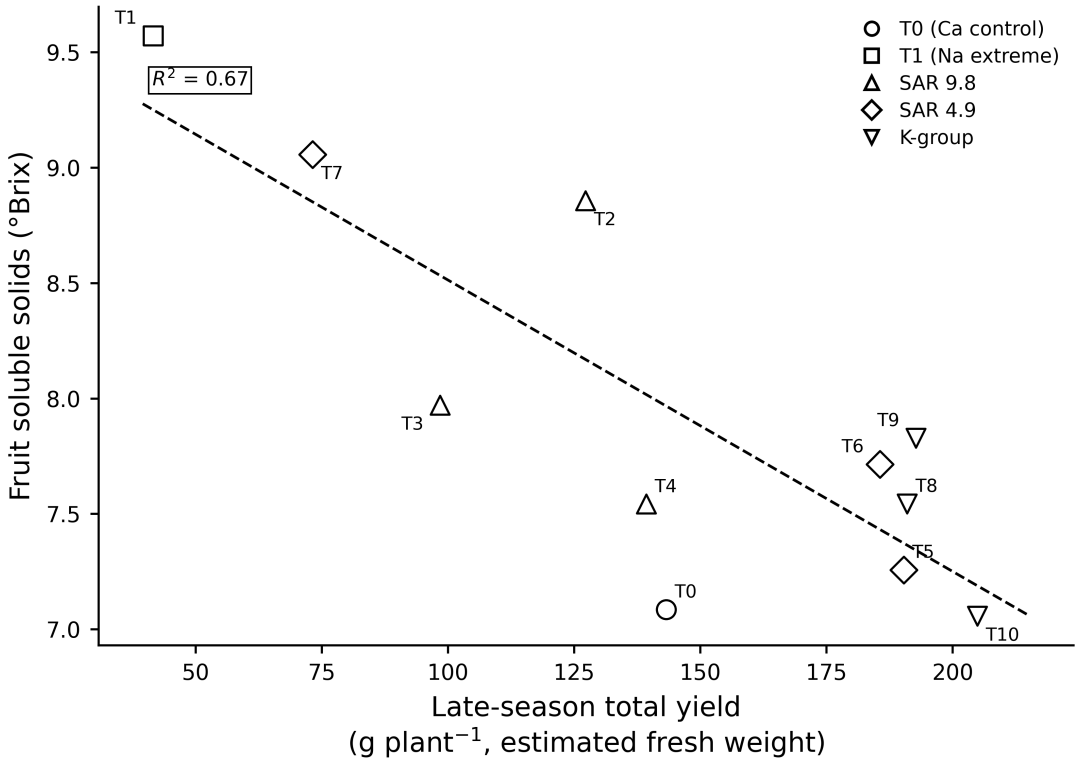


Fig. 5. Relationship between strawberry late-season yield and fruit soluble solids concentration under irrigation waters with contrasting cation composition. Each point represents the mean value for one irrigation treatment. Symbols indicate treatment groups: calcium-dominated control (T0), sodium-dominated extreme (T1), SAR 9.8 group (T2-T4), SAR 4.9 group (T5-T7) and potassium-dominated SAR = 0 group (T8-T10).

Biomass and integrated crop performance

Final shoot biomass reflected the cumulative growth patterns observed in canopy cover and yield. The calcium-dominated control produced the highest fresh and dry biomass, whereas the sodium-dominated extreme treatment produced the lowest biomass. Intermediate treatments showed variable responses depending on their cation composition and CROSSf values.

The consistency among canopy cover, fruit yield and final biomass supports the interpretation that irrigation water cation composition affected whole-plant performance. Because biomass variables were also included in the predictive comparison shown in Fig. 4, they provide additional evidence that CROSSf was more closely related to integrated plant response than SAR.

These results suggest that non-destructive canopy measurements can serve as useful indicators of cumulative plant response under contrasting irrigation water quality conditions, especially when combined with final biomass and yield measurements.

Tissue ion accumulation and cation balance

Plant tissue ion concentrations reflected the ionic composition of the irrigation waters (Fig. 6). Sodium accumulation was highest in plants irrigated with the sodium-dominated treatment, whereas potassium concentrations increased in treatments receiving potassium-rich irrigation water. Calcium and magnesium concentrations also responded to their respective supply in the irrigation treatments.

The tissue ion patterns suggest the occurrence of cation interactions and potential nutrient antagonisms. In particular, elevated sodium or potassium supply may have affected the relative uptake of calcium and magnesium. These responses indicate that irrigation water composition influenced plant performance through both root-zone physical effects and direct plant ion balance.

Chloride accumulated in chloride-based treatments, but no clear visual chloride toxicity symptoms were observed. Therefore, the growth reductions observed under sodic and mixed-cation treatments were more likely associated with impaired root-zone conditions and cation imbalance than with chloride toxicity alone.

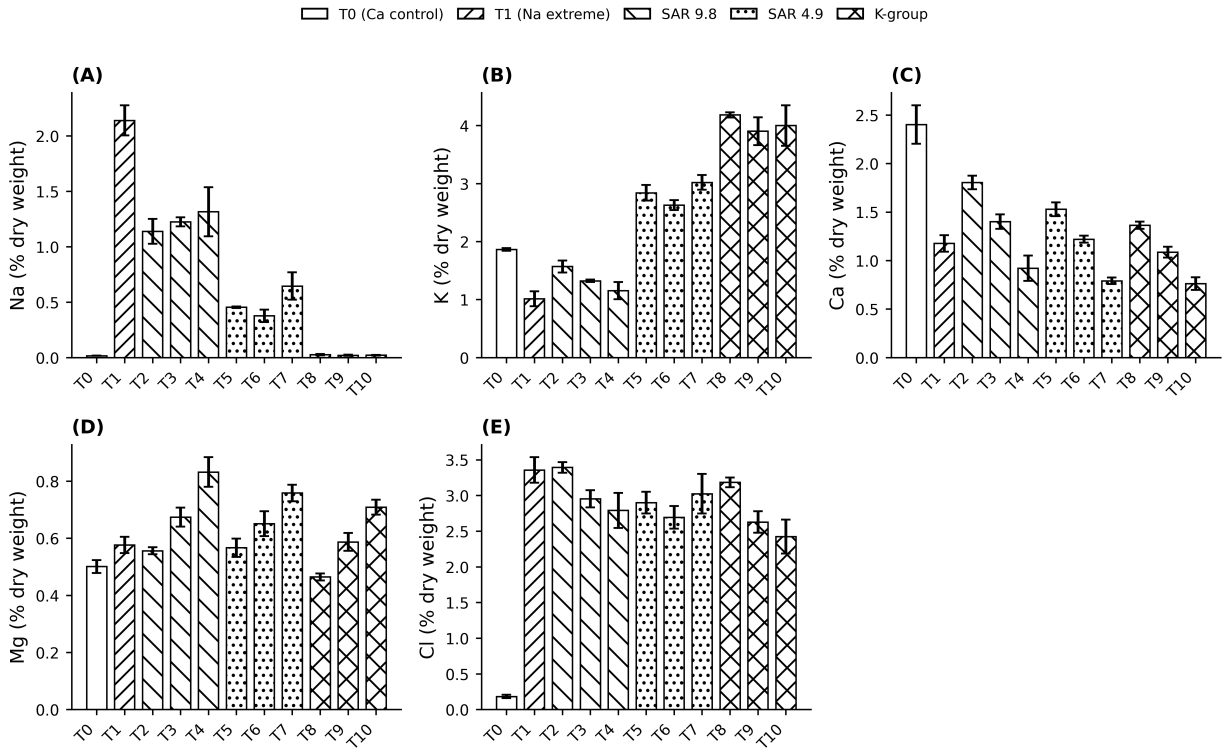


Fig. 6. Strawberry shoot ion accumulation at final harvest under irrigation waters with contrasting cation composition. Panels show concentrations of (A) Na, (B) K, (C) Ca, (D) Mg and (E) Cl. Treatments are ordered from T0 to T10 and grouped as calcium-dominated control (T0), sodium-dominated extreme (T1), SAR 9.8 group (T2-T4), SAR 4.9 group (T5-T7) and potassium-dominated SAR = 0 group (T8-T10). Error bars indicate SD.

Discussion

Strawberry response to multi-cation irrigation waters

The results of this study show that irrigation water cation composition modified both root-zone conditions and strawberry performance. The calcium-dominated control maintained the most favorable root-zone environment and produced the highest canopy cover, biomass and yield, whereas the sodium-dominated treatment increased root-zone water retention, prolonged ponding and strongly reduced plant growth and productivity.

These responses are consistent with the established effects of sodicity on soil physical properties. Sodium promotes clay swelling and dispersion, which can reduce aggregate stability, clog conducting pores, decrease hydraulic conductivity and impair drainage (Quirk and Schofield 1955; Shainberg and Letey 1984; Suarez et al. 2006; Rengasamy 2018). In clay-rich soils containing swelling minerals such as montmorillonite, both clay swelling and clay dispersion may contribute to reduced permeability and poor aeration (Marchuk et al. 2013; Awedat et al. 2021).

The inclusion of volumetric water content, ponding persistence and leachate EC strengthens the interpretation of plant response because it links crop performance with measurable changes in the root-zone environment. This is particularly important in the present study, because the strongest reductions in canopy development and yield occurred in treatments where root-zone conditions also indicated impaired drainage and altered solution chemistry.

Cumulative effects on crop vigor and productivity

Canopy cover and yield differences became more pronounced during the later stages of the experiment. This delayed divergence suggests that the effects of irrigation water cation composition accumulated over time, progressively altering root-zone conditions and plant performance.

Reduced drainage and prolonged ponding can limit oxygen diffusion to roots, causing hypoxic or anoxic conditions that impair root metabolism, nutrient uptake and shoot growth (Armstrong and Drew 2002; Henderson and Patrick 2018). Strawberry is particularly sensitive to poor root-zone conditions because sustained production requires frequent irrigation but also adequate drainage and aeration (Létourneau et al. 2015; Ferreira et al. 2019). Therefore, the reduced canopy development, biomass and yield observed in the sodium-dominated treatment are consistent with a mechanism involving impaired drainage and restricted root aeration.

However, soil physical stress is unlikely to be the only mechanism involved. Sodium and potassium can also affect plant function directly through osmotic stress, ion imbalance and nutrient antagonism (Wakeel 2013; Sardans and Peñuelas 2021). The tissue ion data support this interpretation, particularly the strong sodium accumulation in the sodium-dominated treatment and the evidence of interactions among K, Ca and Mg uptake.

Why SAR alone did not explain crop response

A central finding of this study is that CROSSf provided a more consistent predictor of strawberry response than SAR. This result confirms a key limitation of SAR: it considers sodium relative to calcium and magnesium but does not include potassium and does not distinguish the different flocculating effectiveness of calcium and magnesium (Richards 1954; Rengasamy and Marchuk 2011).

CROSS was developed to better represent multi-cation effects on soil structural stability by incorporating Na, K, Ca and Mg into a single index (Rengasamy and Marchuk 2011). Previous studies have shown that CROSS can improve prediction of clay dispersion, permeability reduction and soil structural instability compared with SAR under waters containing relevant concentrations of K and Mg (Smith et al. 2015; Qadir et al. 2021). The present study extends this concept by showing that CROSSf is also more closely related to crop-level responses, including canopy cover, biomass and yield.

The strongest evidence comes from internal comparisons among treatments with similar SAR but different cation composition. Potassium-dominated treatments with SAR = 0 did not behave like the calcium-dominated control, even though their SAR values were identical. Similarly, within the SAR 4.9 and SAR 9.8 groups, strawberry response varied according to Ca/Mg balance and CROSSf. These comparisons demonstrate that SAR alone can underestimate risk in multi-cation irrigation waters.

CROSSopt did not consistently outperform CROSSf for crop-level responses. This may indicate that the optimized coefficients developed for soil physical thresholds do not necessarily translate directly to plant response variables. Crop performance integrates soil physical constraints, plant ion uptake, root-zone aeration and physiological stress, and therefore may not follow the same relationships as individual soil hydraulic indicators.

Potassium, magnesium and plant ion balance

The potassium-dominated SAR = 0 treatments are particularly important because they illustrate a practical limitation of SAR-based water quality assessment. According to SAR, these treatments would be considered non-sodic because they contained no sodium. However, their canopy and productivity responses differed from the calcium-dominated control, indicating that potassium can contribute to soil structural or physiological constraints when present at elevated concentrations.

Potassium is generally less dispersive than sodium, but it can still influence clay behavior and soil hydraulic properties depending on soil mineralogy, electrolyte concentration and Ca/Mg balance (Chen et al. 1983; Arienzo et al. 2009, 2012; Smith et al. 2015). This is particularly relevant for recycled water irrigation because treated wastewater can contain elevated potassium concentrations derived from domestic, industrial or agricultural sources (Pedrero et al. 2010; Drechsel et al. 2023).

Magnesium effects are also relevant. Although magnesium is a divalent cation, it is generally less effective than calcium in promoting clay flocculation and maintaining soil structural stability (Rengasamy and Marchuk 2011; Smith et al. 2015). The differences observed among Ca-dominated, mixed Ca/Mg and Mg-dominated treatments within the same SAR class support the need to distinguish divalent cation composition rather than treating Ca and Mg as equivalent, as SAR does.

Yield-quality trade-off under severe sodic stress

The sodium-dominated treatment produced the lowest yield but the highest fruit sugar concentration. This indicates a clear trade-off between productivity and fruit quality under severe stress. Increased soluble solids under salt or water stress have

been reported in strawberry and other fruit crops and may be associated with osmotic adjustment, reduced fruit water accumulation or altered carbon partitioning (Keutgen and Pawelzik 2009; Galli et al. 2016; Ma et al. 2022).

This response should not be interpreted as a beneficial effect of sodic irrigation water. In this experiment, higher °Brix occurred together with reduced canopy cover, biomass and fruit production. Therefore, increased soluble solids most likely reflected stress-induced concentration or metabolic adjustment rather than improved crop performance.

This finding has practical relevance for high-value horticultural crops because fruit quality traits may sometimes improve under moderate stress. However, when stress is severe enough to reduce plant growth and marketable yield, any increase in °Brix is unlikely to compensate for productivity losses and potential degradation of soil physical function.

Implications for recycled water use in strawberry production

Traditional assessments based mainly on EC and SAR may underestimate permeability and crop-performance risks when irrigation waters contain elevated K or Mg or when waters are blended from marginal-quality sources (Sposito et al. 2016; Qadir et al. 2021; Drechsel et al. 2023).

The results of this study suggest that using CROSSf alongside SAR could improve risk assessment for strawberry and other high-value crops irrigated with recycled or blended waters. This is particularly relevant in systems where K-rich or Mg-rich waters are used, or where maintaining soil structure and root-zone aeration is critical for crop productivity.

From a management perspective, maintaining adequate calcium availability appears essential for preserving soil structure and supporting crop performance. Strategies such as gypsum application, water blending, adequate leaching and drainage management can help reduce sodicity-related risks (Ayers and Westcot 1985; Rengasamy 2018; Qadir et al. 2021). However, these strategies should be evaluated using indices that reflect the full cation composition of the irrigation water rather than sodium alone.

From an applied perspective, long-term recycled water assessments in California have shown that CROSS can be more responsive than SAR to changes in delivered water quality and soil sodicity indicators, and that sampling depth, drainage conditions and water-source blending strongly influence the interpretation of sodicity risk (Kisekka et al. 2022). Therefore, combining SAR and CROSSf with root-zone monitoring may improve irrigation water quality assessment in systems using recycled or blended waters.

Limitations and future research for horticultural application

This study was conducted under controlled greenhouse conditions using pots, which allowed irrigation water cation composition to be isolated while maintaining constant salinity. This design was appropriate for comparing SAR and CROSSf under controlled conditions, but it limits direct extrapolation to field systems.

The crop responses observed here are consistent with soil physical mechanisms reported in previous laboratory column experiments, where irrigation water cation composition affected clay dispersion and hydraulic conductivity (Aldughaishi et al. 2024). However, because direct measurements of exchangeable cations, hydraulic conductivity and aggregate stability were not the central endpoints of the present crop-response manuscript, these mechanisms should be interpreted as supported by the observed root-zone responses rather than fully demonstrated under the present conditions.

Field and cropping systems may differ from laboratory columns because root growth can modify soil pore architecture and hydraulic behavior (Scholl et al. 2014). In field soils, sodicity effects may develop more slowly and may be influenced by spatial variability, rainfall, soil depth, root distribution, leaching fraction and long-term cation exchange processes.

Future research should validate these findings under multi-season field conditions and include direct measurements of hydraulic conductivity, aggregate stability, exchangeable cations, soil solution chemistry, root traits, redox status and plant physiological responses. These measurements would help separate soil physical effects from direct ion toxicity and support the development of practical CROSS-based thresholds for irrigation water management.

Conclusions

This study demonstrated that irrigation water cation composition significantly influenced strawberry canopy development, yield, fruit quality, biomass and tissue ion accumulation under controlled greenhouse conditions. By using synthetic irrigation waters at constant salinity but contrasting Na, K, Ca and Mg composition, the experiment isolated the effect of cation balance from total salinity.

The calcium-dominated control maintained the most favorable root-zone conditions and produced the highest canopy cover, biomass and fruit yield. In contrast, the sodium-dominated extreme treatment increased root-zone water retention and ponding persistence and produced the lowest crop performance.

Differences among treatments with similar SAR values showed that strawberry response was controlled by broader cation composition rather than sodium alone. In particular, potassium-dominated treatments with SAR = 0 did not behave like the calcium-dominated control, demonstrating an important limitation of SAR-based assessment for recycled or marginal-quality waters.

CROSSf provided a more consistent predictor of strawberry response than SAR, particularly for late-season canopy cover, marketable yield and biomass. These findings support the use of multi-cation indices for interpreting crop responses in high-value horticultural systems where potassium and magnesium concentrations are relevant.

The study also revealed a yield-quality trade-off under severe sodic stress. The sodium-dominated treatment produced fruit with higher soluble solids concentration, but this occurred together with substantial reductions in yield and biomass, indicating a stress response rather than an improvement in overall crop performance.

Overall, irrigation water quality assessment based only on SAR may underestimate risks for strawberry production under multi-cation irrigation waters. Incorporating CROSSf into irrigation management frameworks could improve prediction of crop response and support more robust management of recycled or marginal-quality water in horticultural systems. Field validation over multiple seasons is needed before operational thresholds can be established.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and materials

The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

Conceptualization: I.K., S.R.G., F.P.S. and U.A.; methodology: U.A., S.R.P. and I.K.; formal analysis: U.A., S.R.P. and F.P.S.; writing-original draft: U.A., F.P.S. and I.K.; writing-review and editing: all authors.

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Not applicable.

Supplementary material

Supplementary Fig. S1. Relationship between fresh and dry fruit weight used to estimate fresh fruit mass from dry fruit measurements.

Supplementary Fig. S2. Irrigation schedule during the 40-week greenhouse experiment. The black step line shows daily irrigation volume per plant and the grey line shows approximate cumulative irrigation per plant. The dashed vertical line marks the increase in pulse volume after week 22.

Supplementary Table S1. Yield, fruit quality and final biomass by irrigation treatment. Estimated fresh fruit weight was calculated from the fresh-dry fruit weight relationship: Dry = 0.08059 × Fresh + 0.04215. The late-season period corresponds to weeks 30-40. Values are means ± SD on a per-plant basis.

Supplementary Table S2. Statistical summary of treatment effects on fruit yield, fruit soluble solids, biomass and shoot ion accumulation. ANOVA p-values and Tukey groupings are provided for the main crop-response variables used to support the interpretation of Figs. 3–6.

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