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Integrated physical-biochemical strategy to improve Valencia orange trees salinity resilience, yield and quality under saline irrigation

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Highlights:
- Salinity limits citrus productivity under long-term saline irrigation stress.
- Integrated magnetic water treatment with seaweed biostimulant stress priming.
- Two-year field trial linking physiology, stress markers, yield, and fruit quality.
- Combined treatments improved resilience, yield, and fruit quality.
- Integrated physical-biochemical strategy sustains citrus under saline irrigation.

Abstract: Saline irrigation is a major constraint to citrus production in semi-arid regions, where increasing groundwater salinity threatens long-term orchard sustainability. This study evaluated an integrated physical-biochemical strategy combining magnetically treated saline water (MTSW) with a foliar application of a seaweed-derived biostimulant (*Ascophyllum nodosum*) to mitigate salinity stress in Valencia orange (*Citrus sinensis*) grafted onto 'Volkamer' lemon (*Citrus volkameriana*). A two-year field experiment compared three irrigation regimes: nontreated saline water, MTSW alone, and MTSW supplemented with 10 $cm^3 \cdot dm^{-3}$ of water and *A. nodosum* extract. The combined treatment significantly improved vegetative growth, leaf relative water content, and soluble carbohydrate accumulation, while reducing stress indicators including proline and malondialdehyde. Enhanced physiological status translated into higher fruit yield, greater juice percentage, and increased total soluble solids, accompanied by reduced titratable acidity relative to the saline control. Across both seasons, the integrated treatment consistently outperformed MTSW alone, indicating enhanced effects between altered water properties and biostimulant-mediated metabolic regulation. The results suggest that coupling magnetic water treatment with seaweed biostimulants strengthens osmotic adjustment, membrane stability, and carbon allocation under salinity stress. However, the experiment was unable to include a treatment combining saline irrigation with *A. nodosum* in the absence of magnetic treatment; therefore, the independent contribution of the biostimulant under non-magnetised saline conditions cannot be fully separated from the observed combined effects. Despite this limitation, the findings indicate that this chemical-free, field-validated approach provided a scalable management strategy to sustain citrus productivity and fruit quality under saline irrigation in arid and water-limited production systems.

Keywords: biostimulant, *Citrus sinensis*, magnetic water, saline irrigation, semi-arid agriculture

INTRODUCTION

Soil and water salinity represent major constraints to agricultural productivity, particularly in arid and semi-arid regions where freshwater scarcity necessitates irrigation with saline groundwater (Balba, 2018; Ashraf and Munns, 2022; Abdelsalam *et al.*, 2024). Globally, over one-fifth of the irrigated land is affected by salinisation, driven by low precipitation and high evaporative demand that promote salt accumulation in surface soils and reduce long-term fertility (Richards, 1954; Munns and Tester, 2008). Elevated sodium and chloride concentrations disrupt soil structure, impair hydraulic conductivity, and impose osmotic and ionic stress on crops, ultimately limiting growth and yield (Balal *et al.*, 2012; Ben Mimoun *et al.*, 2017; Ashraf and Munns, 2022).

Perennial fruit systems are particularly vulnerable, as salinity effects accumulate over multiple seasons. Citrus orchards in dry environments frequently experience root-zone salinisation, reduced water uptake, and nutrient imbalance (Maas, 1993; Levy and Syvertsen, 2003). Excess salts interfere with potassium and calcium acquisition, destabilise cellular membranes, and impair photosynthesis, reducing fruit quality and productivity (Zekri and Parsons, 1992; Chatzissavvidis, Papadakis and Therios, 2008; Hassan *et al.*, 2020). Valencia orange is moderately salt-sensitive, and prolonged exposure to saline irrigation can reduce canopy vigour and yield (Maas, 1993).

Conventional reclamation practices, such as gypsum application and leaching, partially mitigate sodicity and electrical conductivity but are limited when saline water remains the primary irrigation source (Balba, 2018). Alternative approaches that improve soil–water interactions and plant physiological resilience are needed to sustain orchard systems under chronic salinity.

Magnetic treatment of irrigation water has emerged as a chemical-free technology capable of modifying water properties and enhancing salt redistribution in the rhizosphere (Hilal and Hilal, 2000; Maheshwari and Grewal, 2009; Bouhlel, Khaskhoussy and Hachicha, 2024). Studies indicate improved crop performance under saline irrigation with magnetic treatment, suggesting enhanced infiltration, nutrient mobility, and osmotic regulation (Hozayn and Abdul-Qados, 2010; Khosrojerdi, Moghaddam and Farhadi, 2023).

In parallel, biostimulants derived from marine algae, particularly *Ascophyllum nodosum* extracts, activate plant stress-defence pathways through polysaccharides, phenolics, and hormone-like compounds that enhance antioxidant capacity, osmotic adjustment, and nutrient uptake (Khan *et al.*, 2009; Colla and Rouphael, 2015; Shukla *et al.*, 2019). Foliar application allows rapid metabolic priming and partially bypasses soil-mediated constraints (Goñi, Quille and O'Connell, 2018; Deolu-Ajayi *et al.*, 2022). Evidence shows improved tolerance to salinity and drought, along with enhanced fruit quality (Bonomelli *et al.*, 2018; Kumari *et al.*, 2021).

Integrating magnetically treated irrigation water with *A. nodosum* biostimulant application represents a dual strategy targeting both root-zone salinity dynamics and canopy-level stress physiology. Limited research has evaluated the combined effect of these physical and biochemical interventions in perennial fruit crops. The objective of this study was to assess whether this integrated approach improves soil-plant-water relations, physiological stability, and fruit productivity of Valencia orange trees irrigated with saline water.

MATERIALS AND METHODS

FIELD EXPERIMENT AND LOCATION

Field trials were carried out at a private farm located along the Cairo–Alexandria Desert Road in Egypt (coordinates: ~30°03'N, 31°13'E), where growers routinely use saline groundwater for irrigation (Tab. 1). This region has sandy soil with limited organic matter and experiences a semi-arid climate, typified by high summer temperatures (up to 38°C), cool winter temperatures (~10°C), and minimal rainfall (<50 mm·y^{-1}). The orchard's sandy soil is prone to salt accumulation due to its low water-holding capacity (Balba, 2018). The study used 10-year-old Valencia orange trees grafted onto Volkamer lemon (*Citrus volkameriana*) rootstock. Trees were spaced 4 m within rows and 6 m between rows. All the recommended agricultural practices were applied as

Table 1. Study area soil chemical analysis in the Cairo-Alexandria Desert Road region, Egypt (2024)

Parameter	Unit	Value
pH	–	7.7
Organic matter	%	0.5
Electrical conductivity	dS·m^{-1}	1.7
Nitrogen (N)	mg·dm^{-3}	30
Phosphorus (P)		22
Potassium (K)		160
Zinc (Zn)		2.7
Iron (Fe)		3.0
Soil texture	–	sandy

Source: own elaboration.

usually recommended by the Egyptian Ministry of Agriculture, including fertilisation and pest control programs. Groundwater was taken up from a well to provide the irrigation supply. A prior analysis indicated that the electrical conductivity (*EC*) was 3.0 $dS \cdot m^{-1}$, the total dissolved solids (*TDS*) were approximately 1920 $mg \cdot dm^{-3}$, potential of hydrogen (pH) of 7.8, and elevated levels of Na^{+}, Cl^{-}, and bicarbonate (HCO_3^{-}). This salinity level exceeds the recommended thresholds for citrus, creating a clear need for mitigation strategies.

The field experiment was arranged as a randomised complete block design with three treatments and 10 replicates. Each experimental unit was a randomly selected tree within the row receiving the irrigation treatment. The three treatments consisted of: (T1) control as saline irrigation water with no modifications (Tab. 2), (T2) magnetically treated saline water (MTSW) as saline irrigation water passed through a magnetic device (~1 tesla (T)), and (T3) MTSW + *A. nodosum* extract solution at 10 $cm^3 \cdot dm^{-3}$ concentration, as saline irrigation water passed through a magnetic device (~8 T), plus foliar applications of biostimulant. However, it was not feasible to include a treatment combining saline irrigation with *A. nodosum* in the absence of magnetic treatment in the experiment; therefore, the independent contribution of the biostimulant under non-magnetised saline conditions cannot be fully separated from the observed combined effects. To obtain magnetic water for T2 and T3, irrigation water was treated using a Magnolith® magnetic device (6-inch, output 130 $m^3 \cdot h^{-1}$, 0.7 T, EWL Umwelttechnik GmbH, Germany) installed on the main irrigation pipeline upstream of the distribution network, ensuring that all irrigation water supplied to the treated trees passed through the magnetic unit before entering the drip irrigation system. The device consists of a series of permanent magnet pairs arranged with alternating north and south poles, generating approximately 88 cascaded magnetic fields with an average magnetic intensity of about 0.8 T, according to the manufacturer's technical specifications. This configuration creates multiple magnetic exposure zones along the water flow path, allowing irrigation water to pass sequentially through alternating magnetic gradients before reaching the irrigation emitters. The irrigation system typically operated at a flow rate of approximately 16.67 $m^3 \cdot h^{-1}$ allowing irrigation water to pass continuously through the magnetic unit during each irrigation event. Under these hydraulic conditions, the exposure time of water inside the magnetic device was estimated to be approximately one second, which was consistent with the operational principles of inline magnetic treatment systems. Because the device was installed directly within the irrigation pipeline, the treated water was delivered to the trees immediately after passing through the magnetic unit during the same irrigation cycle, meaning that the time interval between treatment and irrigation was minimal. To characterise irrigation water quality, key physicochemical parameters, including electrical conductivity (*EC*), pH, and total dissolved solids (*TDS*), were monitored during the experimental period. However, paired measurements immediately before and after magnetic treatment were not systematically recorded for each irrigation event. For T3, nutrient sprays of a ready-made biostimulant (Experimental Algae Unit, National Research Centre (NRC), Dokki, Giza, Egypt) contained *A. nodosum* extract. According to the product specification, the formulation contained the following components: seaweed extract (*Ascophyllum nodosum*) – 11%, free amino acids – 7%, total nitrogen (N) – 4%, phosphorus (P) – 4%, potassium (K) – 3%, activating agents – 1.52%, iron (Fe) – 0.4%, zinc (Zn) – 0.085%, manganese (Mn) – 0.1%, boron (B) – 0.1%, copper (Cu) – 0.02%, polysaccharides, polyphenols, and vitamins. The formulation was applied as a 1% foliar extract solution using a spray volume of 1,190 $dm^3 \cdot ha^{-1}$ (500 dm^3 per feddan[1]), ensuring adequate canopy coverage and uniform distribution of the treatment across the trees. No additional adjuvants were added to the spray solution. A 1000 dm^3 tractor-mounted boom sprayer with a high-pressure pump and multiple fine mist nozzles was used to ensure equal application of *A. nodosum* extract, providing even leaf coverage on upper and lower surfaces. To ensure that the treatment coincided with critical physiological phases of tree development, the biostimulant was applied five times during each growing season according to the following phenological stages:
1) early vegetative growth ~15 March,
2) flowering stage ~10 April,
3) fruit set stage ~5 May,
4) first fruit enlargement stage ~10 June,
5) second fruit enlargement stage ~10 July.

Table 2. Irrigation water chemical analysis in the Cairo-Alexandria Desert Road region, Egypt (2024)

Parameter	Unit	Value
pH	–	7.73
Electrical conductivity	$dS \cdot m^{-1}$	3.0
Total dissolved solids	$mg \cdot dm^{-3}$	1,920
Sodium (Na)	$meq \cdot dm^{-3}$	23.2
Potassium (K)		0.3
Calcium (Ca)		3.0
Magnesium (Mg)		4.0
Chlorine (Cl^{-})		25.0
Sulphate (SO_4^{2-})		1.2
Bicarbonate (HCO_3^{-})		4.0

Source: own elaboration.

These stages represent key periods of plant physiological activity, including canopy development, reproductive processes, and fruit growth. Scheduling the applications at these stages allowed the study to evaluate the influence of the biostimulant across the main phases of crop development.

Irrigation scheduling was based on calculated crop evapotranspiration ($ETc = ETo \cdot Kc$), using locally derived reference evapotranspiration (*ETo*) values and growth-stage-specific crop coefficients (Kc = 0.65–0.80). Meteorological data, including average monthly temperature, relative humidity, and *ETo*, were recorded from the nearest weather station (~5 km from the site) to characterise environmental conditions during the two growing seasons (Tab. 3). Identical irrigation volumes were applied to all treatments to ensure uniform water supply and isolate the effects of magnetic and biostimulant treatments. In addition, soil water status was monitored weekly using a tensiometer system (Model 64xx series, Spectrum Technologies Inc., Aurora, IL, USA) to

[1] 1 feddan = 4,200 m^2.

Table 3. Meteorological data for the two consecutive years 2024 and 2025 at El-Natroun city

Month	Air temperature (°C)			*RH* (%)	Wind speed ($km \cdot h^{-1}$)	Rainfall (mm)	Air temperature (°C)			*RH* (%)	Wind speed ($km \cdot h^{-1}$)	Rainfall (mm)
	max.	min.	mean				max.	min.	mean			
	2024						2025					
Jan	18	8	12	59	13.2	7.3	22	11	15	61	12.1	9.7
Feb	21	9	14	59	13.6	10.8	21	8	14	58	13.0	13.9
Mar	23	8	15	55	15.4	3.6	28	12	19	50	15.0	11.6
Apr	34	14	23	42	15.0	0	31	14	22	46	14.1	0.9
May	35	17	25	43	15.0	0	34	17	25	46	14.7	0
Jun	38	21	29	49	14.1	0	38	21	28	45	14.0	0.9
Jul	39	22	29	49	13.1	0	41	23	31	46	13.2	0
Aug	39	23	30	53	13.2	0	39	22	29	51	13.2	0.2
Sep	37	22	28	55	13.1	0.4	38	22	29	52	13.7	0
Oct	31	19	24	59	12.3	6.9	32	20	25	56	12.9	0.3
Nov	26	15	20	58	11.0	1.4	28	17	21	57	12.5	7.15
Dec	24	13	17	63	11.1	8.8	24	13	17	62	12.1	2.02

Explanations: max. = maximum, min. = minimum, *RH* = relative humidity.
Source: own study.

ensure that irrigation was applied when soil water tension reached the predefined threshold for optimal tree performance. Each tree was supplied with water through two lateral drip irrigation lines positioned on both sides of the tree row. A total of 10 drippers per tree were used, each delivering 4 $dm^3 \cdot h^{-1}$, resulting in a discharge rate of 40 $dm^3 \cdot h^{-1}$ per tree. Drippers were spaced at 30 cm intervals along the irrigation laterals. Irrigation scheduling was dynamically adjusted according to calculated crop evapotranspiration (*ETc*) and soil water tension monitored weekly using tensiometers, resulting in irrigation frequencies ranging from one to five events per week depending on seasonal climatic conditions.

Because irrigation was regulated dynamically according to crop water demand and soil moisture conditions, the exact number of irrigation events varied during the growing season (typically between one and five irrigations per week, depending on climatic conditions). However, all treatments received the same irrigation management regime, ensuring that any observed differences among treatments were attributable solely to the magnetic water treatment and the biostimulant application, rather than to differences in water supply.

Soil samples were obtained from the top 30 cm near the tree root zone. Soil *EC* was determined using the saturated paste extract method (Richards, 1954). The sodium adsorption ratio (*SAR*) was calculated based on Na^+, Ca^{2+}, and Mg^{2+} concentrations, while soil pH was measured in a 1:2.5 soil-to-water suspension (Esmaillou *et al.*, 2024). Soil and water analyses were conducted following standard protocols to maintain methodological consistency (Horwitz, 2000).

DATA COLLECTED

Tree height was measured from the trunk base to the canopy apex. Tree canopy volume was determined by the method and formula that are described in Thorne *et al.* (2002). Leaf area was determined from randomly collected leaves that were scanned and measured with a leaf area meter (Chartzoulakis, 2005). All measurements were recorded at the same phenological stage each season (late summer) to minimise variability due to canopy expansion dynamics.

Fruits were harvested at commercial maturity, when they reached the minimum standards for harvest. Yield was represented by total fruit number and mass (kg) per tree. Fruit drop percentage was calculated using the Equation (1):

$$FDP = \frac{IFN - FFN}{IFN} \cdot 100 \tag{1}$$

where: *FDP* = fruit drop percentage, *IFN* = initial fruit number, *FFN* = final fruit number.

The total fruit mass and yield ($kg \cdot tree^{-1}$) were recorded, and 20-fruit subsamples from each experimental unit were analysed for juice content (%) as a ratio of extracted juice mass to total fruit mass, total soluble solids (*TSS*) measured as degrees Brix using a digital refractometer, and titratable acidity as determined by the NaOH titration method described by the Association of Official Analytical Chemists (Horwitz, 2000).

The relative water content (*RWC*) was determined by the Equation (2):

$$RWC = \frac{\mathrm{FM} - \mathrm{DM}}{\mathrm{TM} - \mathrm{DM}} \cdot 100 \tag{2}$$

where: FM = fresh mass, DM = dry mass, TM = turgid mass.

Leaf proline content was determined by the ninhydrin-based method described by Bates, Waldren and Teare (1973). Leaf malondialdehyde (MDA) was measured using the thiobarbituric acid reaction as described by Munns and Tester (2008). Leaf-soluble sugars were assessed colourimetrically. Abscisic acid (ABA) was measured through an enzyme-linked immunosorbent assay (ELISA). The total phenolic content was determined using the Folin–Ciocalteu assay (Sánchez-Rangel *et al.*, 2013). All biochemical analyses were triplicated to ensure precision, and results were expressed on a fresh mass basis.

STATISTICAL ANALYSIS

The experiment was conducted using a randomised complete block design (RCBD) under field conditions during two consecutive growing seasons. Data collected from the experimental treatments were analysed using statistical package for the social sciences (SPSS) software (ver. 25, IBM Corp., Armonk, NY) for analysis of variance (ANOVA) in accordance with the experimental design in order to evaluate the significance of treatment effects. When significant differences among treatments were detected, the means were separated using Duncan's multiple range test at the 5% probability level ($p \leq 0.05$).

Prior to performing the statistical analysis, the dataset was examined to ensure that the basic assumptions required for ANOVA were reasonably satisfied. In particular, the data distribution and residual patterns were evaluated to verify approximate normality and homogeneity of variances, which are standard conditions for applying parametric statistical tests in agricultural field experiments. Subsequently, Pearson correlation analyses were conducted to explore the relationships among physiological, biochemical, and yield-related traits along with a heatmap in JMP Student Edition 18.2.0 (SAS Institute Inc., Cary, NC, USA). The correlation matrix was created using OriginPro 2021 software, with significance levels indicated as $p < 0.05$ (*), $p < 0.01$ (**), and $p < 0.001$ (***). Furthermore, the hierarchical clustering heatmap was created using the online platform for plotting and clustering SRPLOT (NewCore Biotech, 2025) to visualise and relate the relationships between the factors and the studied treatments.

RESULTS

VEGETATIVE GROWTH RESPONSES

Vegetative growth parameters, including tree height, canopy volume, and leaf area, were significantly influenced by irrigation and foliar treatments across both growing seasons (Fig. 1). Trees receiving T3 consistently produced superior growth compared with control and T2 trees. In 2024 and 2025, trees receiving T3 exhibited the greatest tree height (3.55 and 3.60 m), canopy volume (9.65 and 9.80 m^3), and leaf area (212.5 and 215.0 cm^2), respectively. Among these variables, only leaf area differed significantly between seasons, whereas tree height and canopy volume remained relatively stable across years. Leaf area was significantly higher under T3 in both seasons compared with the control and T2. In addition, the interannual increase in leaf area was comparable between T2 (1.3%) and T3 (1.2%), indicating that magnetic water treatment alone partially alleviated salinity effects on leaf expansion.

PHYSIOLOGICAL RESPONSES

Physiological indicators, including relative water content (*RWC*), leaf soluble sugars, proline, and malondialdehyde (MDA), responded significantly to treatment across both seasons (Fig. 2). Trees receiving T3 exhibited the highest *RWC* values, reflecting improved plant water status and hydration. Leaf soluble sugars,

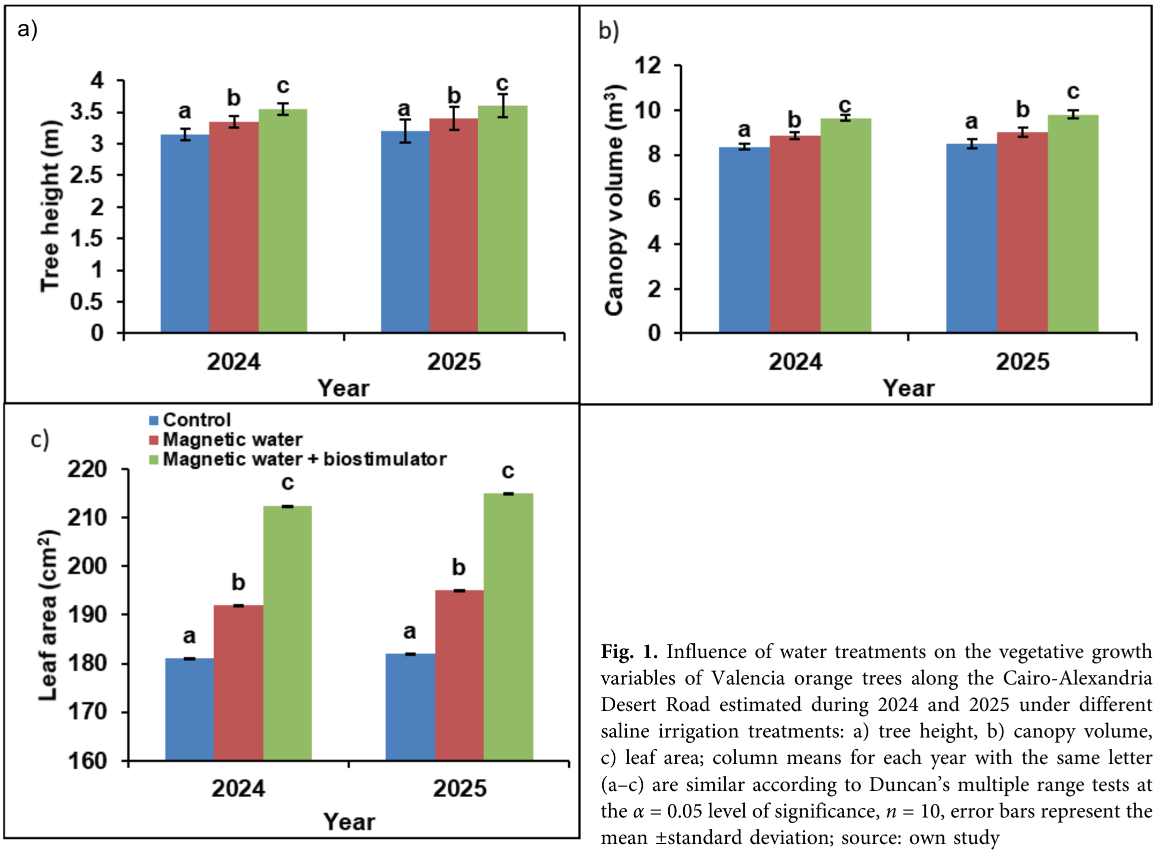

Fig. 1. Influence of water treatments on the vegetative growth variables of Valencia orange trees along the Cairo-Alexandria Desert Road estimated during 2024 and 2025 under different saline irrigation treatments: a) tree height, b) canopy volume, c) leaf area; column means for each year with the same letter (a–c) are similar according to Duncan's multiple range tests at the $\alpha = 0.05$ level of significance, $n = 10$, error bars represent the mean ±standard deviation; source: own study

which contribute to osmotic adjustment and metabolic energy supply, were also significantly elevated under the combined treatment. In contrast, proline accumulation, an indicator of osmotic stress, was highest in control trees irrigated with untreated saline water and was significantly reduced under the combined treatment. Similarly, MDA content, a marker of lipid peroxidation and oxidative stress, was lowest in trees receiving T3, indicating reduced membrane damage under saline conditions.

BIOCHEMICAL RESPONSES

Biochemical parameters, including leaf abscisic acid (ABA) concentration and total phenolic content, showed consistent enhancement under the combined treatment across both growing seasons (Fig. 3). Leaf ABA levels were significantly higher in trees treated with T3 compared with control trees and those receiving magnetically treated saline water (MTSW) alone. Total phenolic

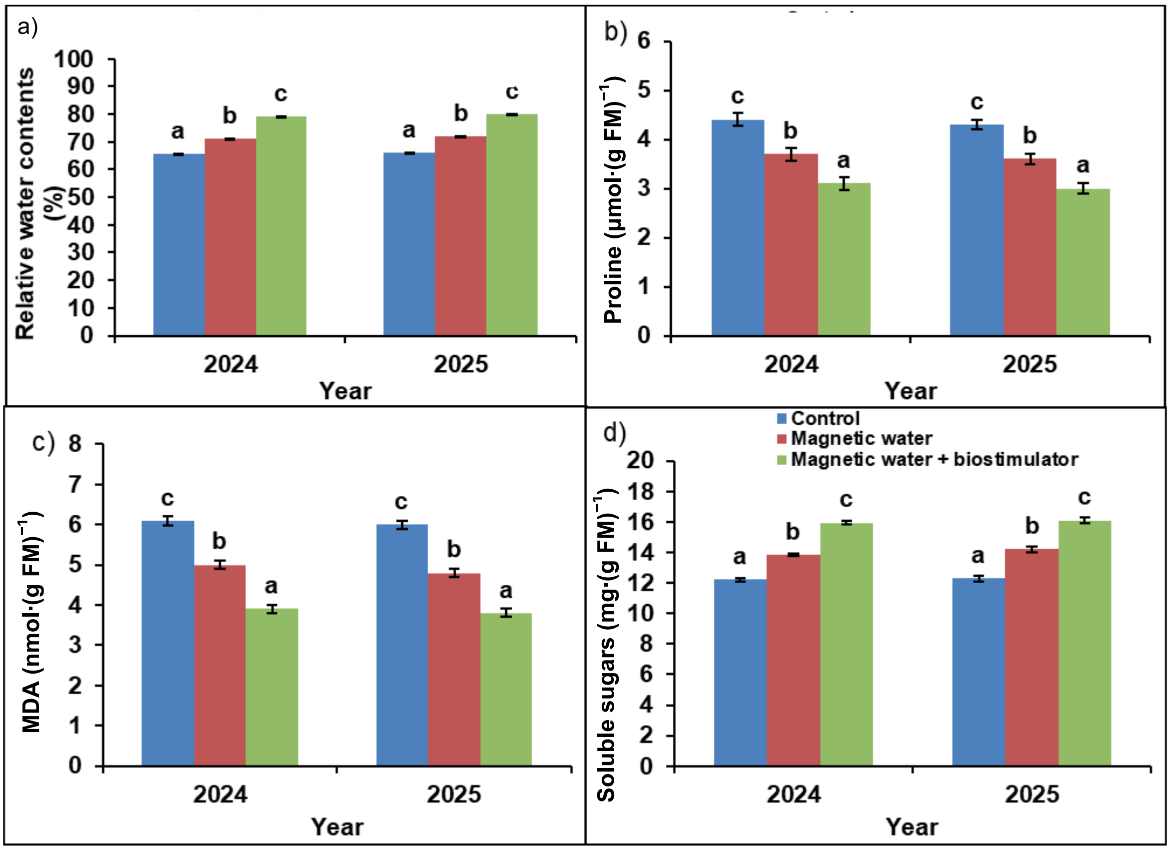

Fig. 2. Influence of water treatments on the physiological variables of Valencia orange trees along the Cairo-Alexandria Desert Road during 2024 and 2025 under different saline irrigation treatments: a) relative water contents, b) proline, c) malondialdehyde (MDA), d) soluble sugars; FM = fresh mass, column means for each year with the same letter (a–c) are similar according to Duncan's multiple range tests at the α = 0.05 level of significance, n = 10, error bars represent the mean ±standard deviation; source: own study

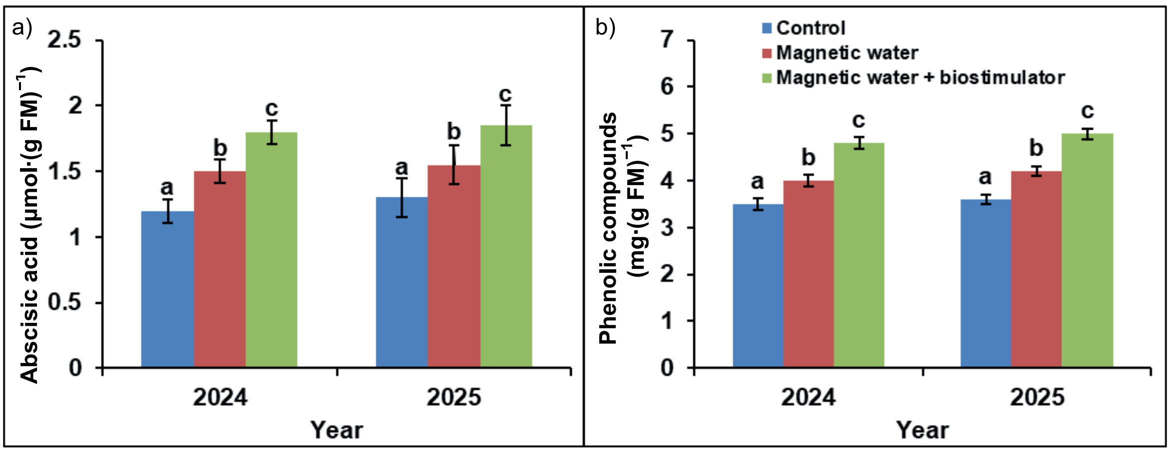

Fig. 3. Influence of water treatments on the biochemical variables of Valencia orange trees along the Cairo-Alexandria Desert Road during 2024 and 2025 under different saline irrigation treatments: a) abscisic acid, b) phenolic compounds; FM = fresh mass, column means for each year with the same letter (a–c) are similar according to Duncan's multiple range tests at the α = 0.05 level of significance (n = 10), error bars represent the mean ±standard deviation; source: own study.

content increased markedly under the combined treatment, reaching 4.90 mg·(g FM)$^{-1}$ compared with 3.55 mg·(g FM)$^{-1}$ in control trees, indicating enhanced antioxidant capacity.

YIELD AND FRUIT QUALITY

Total fruit yield was significantly increased by both MTSW alone and its combination with foliar *A. nodosum* extract compared with the control (Fig. 4). The greatest yield improvement was observed in 2025 under the combined treatment. Fruit *TSS* were significantly higher in trees receiving T3 (Fig. 5). Fruit acidity was significantly reduced under both magnetic water treatments, with the greatest reduction recorded in 2025, indicating an improved sugar–acid balance.

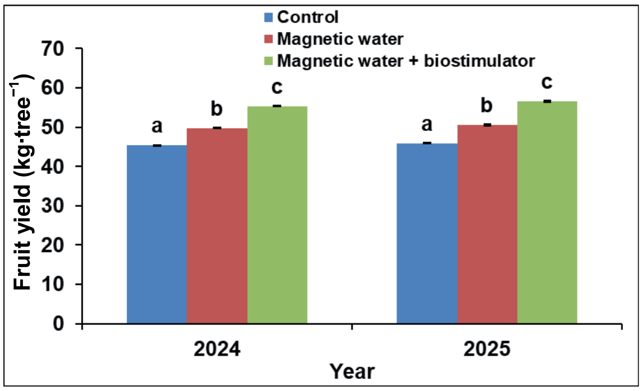

Fig. 4. Fruit yield (kg·tree^{-1}) of Valencia orange trees along the Cairo-Alexandria Desert Road during 2024 and 2025 under different saline irrigation treatments; column means for each year with the same letter (a–c) are similar according to Duncan's multiple range tests at the α = 0.05 level of significance, n = 10, error bars represent the mean ±standard deviation; source: own study

CORRELATION ANALYSIS

Pearson correlation analysis revealed strong relationships among growth, physiological, biochemical, and yield-related variables (Fig. 6). Fruit yield was positively correlated with leaf area, *RWC*, and *TSS* ($p \leq 0.05$), emphasising the importance of improved water status and carbohydrate accumulation for productivity. Phenolic content was positively correlated with *RWC* and negatively correlated with MDA ($p \leq 0.05$), supporting its protective role under salt stress. Leaf MDA exhibited significant negative correlations with fruit yield, fruit mass, leaf area, canopy volume, and tree height ($p \leq 0.05$), emphasising its association with oxidative damage. Fruit acidity was negatively correlated with total soluble sugars and juice percentage ($p \leq 0.05$), consistent with the observed improvements in fruit quality.

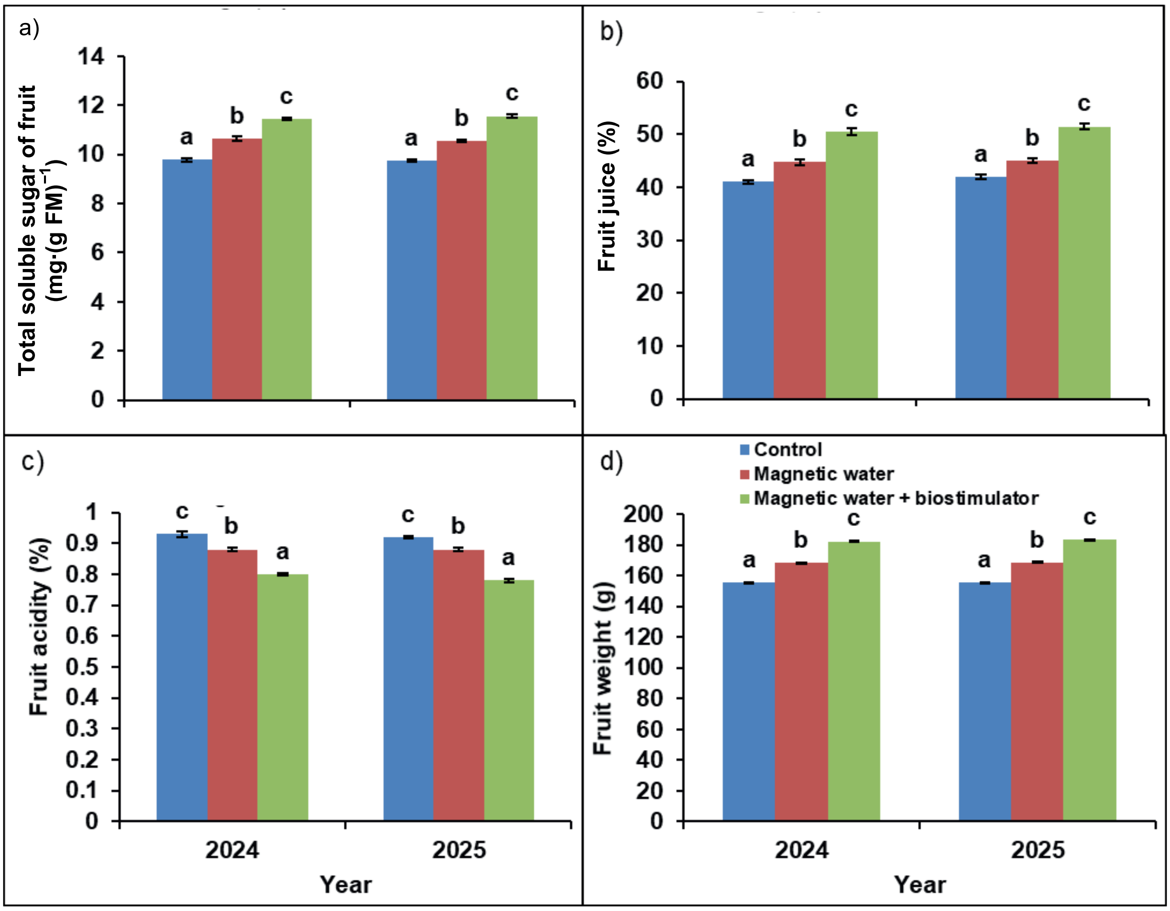

Fig. 5. Influence of water treatments on measured fruit parameters of Valencia orange trees along the Cairo-Alexandria Desert Road during 2024 and 2025: a) total soluble sugar of fruit, b) fruit juice, c) fruit acidity, d) fruit mass; column means for each year with the same letter (a–c) are similar according to Duncan's multiple range tests at the α = 0.05 level of significance, n = 10, error bars represent the mean ±standard deviation; source: own study

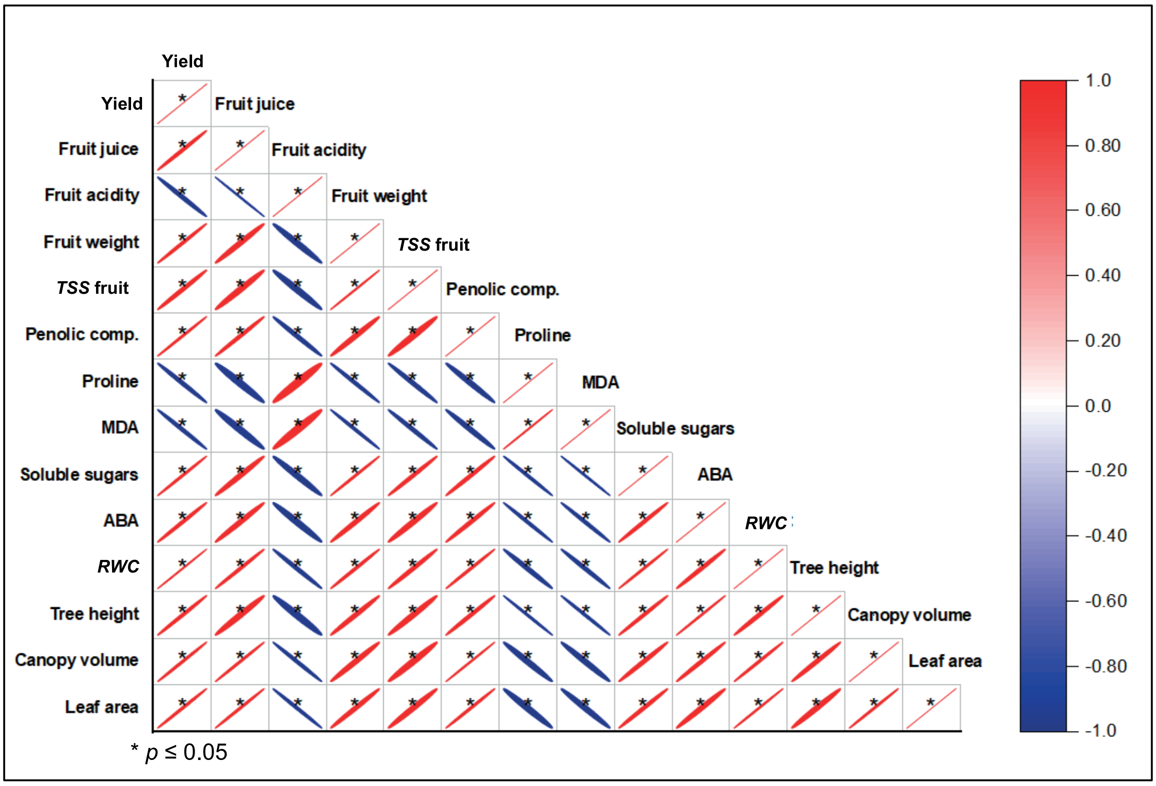

Fig. 6. Pearson correlation matrix shows the relationships among growth, physiological, biochemical, and yield-related attributes of Valencia orange trees along the Cairo-Alexandria Desert Road during 2024 and 2025 under different saline irrigation treatments; red = positive correlation, blue = negative correlation, the intensity of the colour represents the magnitude of the correlation coefficient, *TSS* fruit = fruit total soluble solids, MDA = malondialdehyde contents, ABA = abscisic acid, *RWC* = leaf relative water content; source: own study.

CLUSTER ANALYSIS

Heatmap clustering analysis demonstrated clear treatment-dependent associations among measured variables (Fig. 7). Stress-related traits, including fruit acidity, MDA, and proline, clustered positively with saline water irrigation (control) and negatively with the combined treatment. In contrast, growth, physiological, biochemical, and yield traits, including ABA concentration, phenolics, *RWC*, leaf area, *TSS*, fruit mass, and yield, formed a distinct cluster positively associated with magnetic water plus *A. nodosum* extract and negatively associated with the control. Minor year-specific variation was observed for fruit juice percentage, which showed a stronger positive association with the combined treatment in 2025.

DISCUSSION

Salinity stress reduces citrus productivity by imposing osmotic and ionic constraints that disrupt water relations, nutrient balance, and photosynthesis (Levy and Syvertsen, 2003; Munns and Tester, 2008). Progressive salt accumulation in orchard soils intensifies root-zone stress and compromises long-term sustainability (Balba, 2018). The present findings show that combining magnetic treatment of saline water with foliar *A. nodosum* application mitigates these constraints through coordinated mechanisms at soil and plant levels, although leaf or soil ion data (Na^+, Cl^-, K^+, Ca^{2+}) and seasonal changes in soil *EC* measurements were not part of the current study.

Magnetic water treatment has been shown to improve infiltration, salt redistribution, and ion mobility in saline soils (Hilal and Hilal, 2000; Maheshwari and Grewal, 2009). Magnetic treatment was not expected to reduce water salinity directly, rather the enhanced relative water content observed here supports previous reports that magnetic treatment may influence certain physical properties of water, such as surface tension or viscosity which reduces osmotic limitation and improves root-zone hydration (Hozayn and Abdul-Qados, 2010; Khosrojerdi, Moghaddam and Farhadi, 2023). Improved soil–water interactions likely facilitated nutrient uptake and maintained canopy turgor under saline conditions even though direct nutrient uptake measurements were beyond the scope of this study.

Biostimulant-induced stress tolerance is largely attributed to activation of antioxidant defence systems and metabolic signalling networks (Colla and Rouphael, 2015; Shukla *et al.*, 2019). Reduction in oxidative markers and enhanced osmotic regulation align with transcriptomic and physiological evidence that *A. nodosum* extracts regulate stress-responsive genes and hormonal pathways (Khan *et al.*, 2009; Jithesh *et al.*, 2019; Saeger De *et al.*, 2019). Increased phenolic accumulation suggests reinforcement of cellular redox buffering, a key component of salinity adaptation (Sharma *et al.*, 2019).

The enhanced response under combined treatment indicates that physical modification of irrigation water and biochemical priming jointly contributed to improved plant performance. Magnetic treatment has been shown to improve the rhizosphere environment, while foliar biostimulants stabilise canopy metabo-

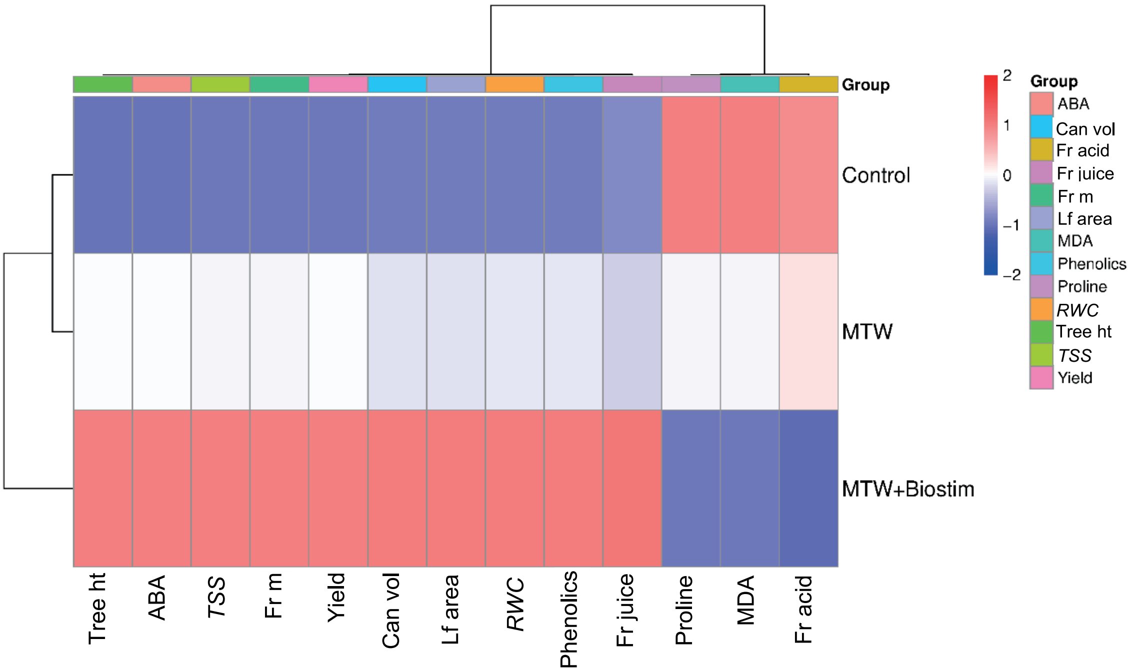

Fig. 7. Heatmap illustrating the hierarchical clustering of growth, physiological, bio-chemical, and yield-related attributes of Valencia orange trees along the Cairo-Alexandria Desert Road averaged over 2024 and 2025 with irrigation treatments; red = positive correlation, blue = negative correlation, the intensity of the colour represents the magnitude of the correlation, Can vol = canopy volume, Fr acid = fruit acid, Fr juice = fruit juice, Fr m = fruit mass, Lf area = leaf area, Tree ht = tree height, MTW = magnetically treated saline water, MTW+biostim = magnetically treated saline water plus 10 $cm^3 \cdot dm^{-3}$ of water *A. nodosum* biostimulator extract *RWC*, ABA, MDA, *TSS* as in Fig. 6; source: own study

lism and enhance stress memory (Goñi, Quille and O'Connell, 2018; Rouphael and Colla, 2020; Deolu-Ajayi *et al.*, 2022).

Yield and fruit quality improvements are significant for orchard management. Enhanced soluble solids and reduced acidity indicate better carbohydrate partitioning under stress, consistent with studies linking biostimulants to improved fruit composition (Bonomelli *et al.*, 2018; Kumari *et al.*, 2021). Maintaining productivity under saline irrigation is essential in water-limited regions where conventional reclamation is impractical.

Long-term adoption of integrated physical–biochemical strategies could contribute to sustainable orchard management in salt-affected environments. Extended trials are needed to evaluate cumulative soil physicochemical changes, nutrient cycling, and economic feasibility under commercial conditions. Understanding the persistence of magnetic treatment effects and repeated biostimulant applications will be critical for developing regionally adapted management protocols.

CONCLUSIONS

Salinity stress poses a major challenge to citrus production, particularly in sandy soils irrigated with saline water, where it limits tree growth, fruit quality, and overall yield. This study demonstrated that combining magnetically treated saline irrigation water with foliar applications of *A. nodosum* extract effectively enhanced salinity tolerance in Valencia orange trees. The integrated treatment improved critical physiological and biochemical traits such as relative water content, osmotic regulation, and antioxidant capacity, while also increasing fruit yield, fruit mass, juice content, and total soluble solids, and reducing fruit acidity. These benefits were consistently greater than those achieved with magnetic water treatment alone, highlighting the combined effects of physical and biochemical interventions. Overall, the results suggest that coupling root-zone water modification with canopy-level biochemical priming offers a practical, low-input approach to sustain citrus productivity and quality under saline conditions. This strategy is particularly relevant for arid and semi-arid regions that rely on saline groundwater, offering a scalable means to enhance the resilience of perennial fruit production under climate variability. Future research should investigate the long-term impacts on soil properties, nutrient dynamics, and the economic feasibility of large-scale adoption.

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CONFLICT OF INTERESTS

All authors declare that they have no conflict of interests.

INSTITUTIONAL REVIEW BOARD STATEMENT

No animal research was conducted.

The authors complied with the Convention on Biological Diversity and the Convention on the Trade in Endangered Species of Wild Fauna and Flora.

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