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RESEARCH ARTICLE

Revolutionizing sugar beet yield and quality in saline sandy soil through synergistic humic acid, glauconite, and boron foliar application

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Abstract

Aims Saline sandy soils severely constrain sugar beet (*Beta vulgaris* L.) productivity due to low nutrient retention, high salinity, and micronutrient imbalances, particularly boron deficiency. Although humic substances, glauconite, and boron fertilization have individually or pairwise improved crop performance, no previous field study has evaluated their ternary, dose-optimized integration as a multifunctional soil–plant management strategy under saline sandy conditions.

Methods This study investigated, for the first time, the combined application of soil-applied humic acid (600 kg/ha), glauconite (1100 kg/ha), and graded foliar boric acid (0, 1900, and 3800 g/ha) to test the hypothesis that their complementary physicochemical and physiological mechanisms would generate synergistic improvements in soil quality, crop performance, and sugar productivity beyond additive effects. Field experiments were conducted over two consecutive growing seasons (2021–2022) in West Minya, Egypt, using a split-plot design.

Results The integrated high-dose treatment (HG3800) significantly enhanced leaf area index (by 75%), chlorophyll content (46–71%), and net photosynthetic rate (40–128%) relative to the control. Root yield increased by 27% (reaching 56.7 ton/ha), while sugar yield rose by up to 79% (11.5 ton/ha). Sucrose concentration reached 20.4%, with reduced impurity indices and improved extractable sugar percentage (up to 90%). Based on fermentable sugar yield, the HG3800 treatment corresponded to a substantial increase in theoretical bioethanol output potential

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per hectare. Concurrently, soil electrical conductivity declined by 24%, soil organic matter increased, and bulk density decreased, reflecting improved soil structure and salinity mitigation.
Conclusions The ternary, dose-optimized integration of humic acid, glauconite, and foliar boron represents a novel agronomic strategy that simultaneously enhances soil physicochemical properties, physiological efficiency, and fermentable sugar production. By directly linking yield gains to increased bioethanol feedstock potential, this approach offers a scalable and multifunctional pathway for sustainable bioenergy-oriented sugar beet production in salt-affected sandy soils.

Keywords Sugar beet · Soil amendments · Soil reclamation · Foliar application · Soil quality · Sustainable agriculture

Introduction

Sugar beet (*Beta vulgaris* L.) is a major sugar-producing crop, contributing approximately 20% of global sugar production and serving as an important feedstock for bioethanol and animal feed (Stevanato et al. 2019; Tayyab et al. 2023). Its relatively short growing cycle and adaptability make it suitable for regions where sugarcane cultivation is limited. However, production in saline sandy soils remains constrained by poor water-holding capacity, low cation exchange capacity (CEC), nutrient leaching, and salinity stress (Abbas et al. 2018; Shabana et al. 2024). These limitations reduce nutrient availability, impair photosynthesis, and ultimately decrease root yield and sucrose accumulation.

Organic and mineral soil amendments have been proposed to mitigate these constraints. Humic acid improves soil structure, increases soil cation exchange capacity (CEC), enhances nutrient retention, and stimulates root growth under stress conditions (Shabana and Shawky 2020; Thalooth et al. 2020). By increasing CEC, improving aggregate stability, and enhancing water-holding capacity, humic acid improves soil moisture retention and reduces rapid water percolation in sandy soils. In addition, humic substances stimulate root proliferation, increase root surface area, and promote osmotic adjustment and antioxidant defense systems in plants under drought conditions. These combined soil and physiological effects enhance nutrient uptake and help mitigate the impacts of water and nutrient stress in sandy environments (Abbas et al. 2018; Thalooth et al. 2020).Glauconite, a potassium-rich clay mineral, functions as a slow-release fertilizer and soil conditioner, improving K supply, porosity, and salinity tolerance (Rudmin et al. 2020; Shabana et al. 2024). While both amendments enhance soil fertility and crop performance, their combined effects in saline sandy soils remain insufficiently explored.

Micronutrient deficiency, particularly boron (B), further limits sugar beet productivity in sandy soils with low organic matter. Boron plays a key role in cell wall formation, carbohydrate metabolism, and sugar translocation (Dordas et al. 2007). Foliar B application has been shown to improve sucrose concentration and reduce technological impurities (Armin and Asgharipou 2011; Bîlïr and Saltali 2023). However, responses to B are dose-dependent and may interact with soil amendment strategies, particularly where nutrient retention and salinity mitigation are simultaneously targeted.

Despite evidence supporting individual applications of humic acid, glauconite, or boron, limited research has evaluated their integrated use under field conditions in saline sandy soils. Understanding

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whether combined applications produce additive or synergistic improvements in growth, yield, and quality is essential for developing sustainable management strategies in marginal environments.

Although previous studies have demonstrated yield improvements from individual amendments or pairwise combinations, no study to date has systematically evaluated the ternary integration of humic acid (Abbas et al. 2018), glauconite, and graded foliar boron under saline sandy soil conditions (Shabana et al. 2024). Existing strategies typically target isolated constraints—such as organic matter deficiency (humic acid), potassium limitation and salinity (glauconite), or micronutrient imbalance (boron)—without addressing their interactive soil–plant feedbacks. We propose that integrating these amendments may generate synergistic rather than merely additive effects by concurrently enhancing cation exchange capacity, stabilizing nutrient release, improving boron uptake efficiency, and mitigating sodium-induced ionic stress. This integrated framework represents a conceptual shift from single-constraint correction toward multifunctional soil–plant system optimization.

Despite these advances, the optimal combination and dosage of humic acid, glauconite, and boron for sugar beet cultivation in sandy soils remain underexplored. Previous studies have primarily focused on individual amendments or pairwise combinations, with limited research on the integrated effects of humic acid, glauconite, and varying boron levels (Nemeat-Alla et al. 2021; Shabana et al. 2024). Moreover, the interaction between these treatments and their impact on growth, yield, and quality parameters under field conditions requires further investigation to develop sustainable and cost-effective management practices (Zhang et al. 2025a). The need for such research is particularly urgent in regions like Egypt, where sandy and reclaimed soils dominate agricultural landscapes, and water and nutrient use efficiency are critical for sustainable production (Abbas et al. 2018; Tayyab et al. 2023).

Therefore, this study was designed to test a mechanistic and agronomic framework for synergistic soil amendment integration in saline sandy soils. The specific objectives of the current study were to: (1) quantify the interactive effects of humic acid, glauconite, and graded foliar boron on sugar beet growth, physiology, and yield components; (2) determine whether the ternary combination produces synergistic gains in sugar yield and quality beyond pairwise or individual treatments; and (3) evaluate associated improvements in soil chemical properties relevant to salinity mitigation and nutrient retention.

We tested the following hypotheses: (H1) humic acid and glauconite jointly enhance soil physicochemical properties (CEC, salinity balance, organic matter stabilization), thereby improving root development and biomass accumulation; (H2) foliar boron optimizes sucrose metabolism and reduces quality-limiting impurities under saline stress; and (H3) the integrated application of humic acid, glauconite, and optimized boron generates synergistic improvements in yield, sugar recovery, and soil quality that exceed additive expectations due to complementary mechanisms of chelation, slow nutrient release, and ionic regulation.

Consequently, this study aims to provide the first field-scale evaluation of a ternary, dose-optimized amendment strategy designed to simultaneously improve soil health, physiological efficiency, and fermentable sugar productivity of sugar beet grown in saline sandy soils.

Materials and methods

Experimental site and design

Field experiments were conducted at the research farm of West Minya, Minya Governorate, Egypt (latitude 28.24°N, longitude 29.59°E, elevation 134 m above sea level), during the 2020/2021 and 2021/2022 growing seasons (Figure S1; Supplementary materials). Physicochemical properties of the experimental soil are depicted in Table 1. The study evaluated the effects of leonardite-based humic acid, glauconite, foliar boron application, and their combinations on the growth, yield, and quality of sugar beet (*Beta vulgaris* L., var. Avantage) under drip irrigation in sandy soil. A split-plot randomized complete block design with four replications was employed. The main-plot factor consisted of soil amendment treatments with four levels: (1) Control (no amendment), (2) Humic acid (HA), (3) Glauconite (GL), and (4) Humic acid + Glauconite (HA + GL). The sub-plot factor consisted of three foliar boric acid doses: 0, 1900, and 3800 g/ha. The factorial combination of the four main-plot treatments and three sub-plot boron

Table 1 Mean values for some physical and chemical properties of the experimental soil (0–30 cm) before cultivation in 2021 and 2022 season

Character		2021	2022
pH (1:2.5 Soil:water suspension)		7.77 ± 0.02	7.75 ± 0.01
EC_e (dS/m) (Soil paste extract)		6.26 ± 0.04	5.87 ± 0.03
SAR		2.25 ± 0.09	2.17 ± 0.07
ESP (%)		2.01 ± 0.01	1.91 ± 0.01
Available nutrients (mg/kg)	N	22.7 ± 0.21	25.3 ± 0.19
	P	7.3 ± 0.02	7.9 ± 0.04
	K	163 ± 34	162 ± 25
	B	0.22 ± 0.01	0.19 ± 0.01
SOM (%)		0.46 ± 0.02	0.49 ± 0.01
$CaCO_3$ (%)		12.86 ± 0.91	13.43 ± 0.82
Particle size distribution (%)			
Sand		88.15 ± 0.21	87.82 ± 0.19
Silt		8.73 ± 0.10	8.76 ± 0.09
Clay		3.12 ± 0.01	3.42 ± 0.02
Texture class		Sandy	Sandy
Field capacity (%)		13.8 ± 0.04	15.5 ± 0.05
Wilting point (%)		5.22 ± 0.03	7.25 ± 0.02
Bulk density (g/cm^3)		1.65 ± 0.01	1.64 ± 0.01
Total porosity (%)		37.74 ± 0.99	38.11 ± 0.89
Penetration resistance (N/cm^2)		180 ± 11	170 ± 14
Mn (ppm)		18.51 ± 0.18	17.26 ± 0.20
Fe (ppm)		5.4 ± 0.02	6.2 ± 0.03
Zn (ppm)		0.15 ± 0.01	0.14 ± 0.01

levels resulted in twelve treatment combinations: C0, H0, G0, HG0, C1900, H1900, G1900, HG1900, C3800, H3800, G3800, and HG3800. Each sub-plot measured 28.8 m^2 and consisted of eight ridges, each 6.0 m long and 0.60 m wide. The total plot area was calculated as: 8 ridges × 6.0 m × 0.60 m = 28.8 m^2. Plants were spaced at 0.20 m between hills within each ridge. The experiments included 12 treatments: C0 (control + 0 boric acid), H0 (humic acid + 0 boric acid), G0 (glauconite + 0 boric acid), HG0 (humic acid + glauconite + 0 boric acid), C1900 (control + 1900 boric acid), H1900 (humic acid + 1900 boric acid), G1900 (glauconite + 1900 boric acid), HG1900 (humic acid + glauconite + 1900 boric acid), C3800 (control + 3800 boric acid), H3800 (humic acid + 3800 boric acid), G3800 (glauconite + 3800 boric acid), and HG3800 (humic acid + glauconite + 3800 boric acid). All agronomic practices, irrigation scheduling, and fertilization procedures were standardized across treatments to minimize confounding variability and enhance reproducibility of the experimental framework.

Plant material and cultivation

Multi-germ sugar beet seeds were sourced from the Canal Sugar Plant, Minya–Malawi, Egypt. Seeds were sown in the first week of October during both seasons, with harvesting at 180 days after planting. Plants were thinned at the four-leaf stage to maintain one plant per hill.

Soil amendments and fertilization

Application rates of humic acid, glauconite, and boric acid were selected based on published recommendations for sugar beet in sandy and saline soils, local Egyptian field conditions, and preliminary pot experiments conducted in 2020. These trials used the same cultivar under comparable saline sandy soil conditions, with three replicates per rate, and evaluated early growth, nutrient uptake, and visual phytotoxicity at 60 days after sowing to identify effective and safe dose ranges.

Leonardite-based humic acid (60–80% humic substances, pH 5.5–6.5) was applied at 600 kg/ha. This rate falls within the 500–1000 kg/ha range reported to improve soil cation exchange capacity, water retention, and nutrient uptake in sandy soils (Abbas et al. 2018; Thalooth et al. 2020), and was confirmed in our preliminary trials to deliver significant benefits (e.g., 15–20% CEC increase) without diminishing returns. The granular product (85% purity) was sourced from certified local suppliers, broadcast uniformly, and incorporated into the top 0–0.20 m soil layer via rotary tillage 14 days before sowing.

Glauconite (5–8% K_2O), sourced from the Bahariya Oasis, was applied at 1100 kg/ha. This dosage aligns with studies showing enhanced potassium availability, sustained release, salinity mitigation, and yield improvements in saline soils at 1000–1500 kg/ha (Shabana et al. 2024), while our trials verified adequate K supply (up to 50 mg/kg soil over 180 days) without excessively raising soil electrical conductivity.

Foliar boric acid (17% B), sourced from Elgomhuriya Company, was applied at 0, 1900, or 3800 g/ha in two equal sprays at 65 and 85 days after sowing to

establish a dose–response gradient. These rates were chosen lower than some prior studies to ensure safety under saline stress; preliminary trials showed 1900 g/ha effectively alleviated deficiency symptoms, while 3800 g/ha maximized sucrose accumulation and physiological performance without visible leaf injury (Armin and Asgharipou 2011; Bïlïr and Saltali 2023).

These rates collectively balance agronomic effectiveness, crop safety, environmental considerations, and economic feasibility under Egyptian saline sandy soil conditions. Additional characteristics of the humic acid and glauconite are provided in Tables S1 and S2 (Supplementary materials).

Fertilization followed recommendations from the Ministry of Agriculture and Land Reclamation, Egypt. Phosphorus was applied as calcium superphosphate (15% P_2O_5) at 476 kg/ha during seedbed preparation. Nitrogen was supplied as ammonium nitrate (33.5% N) at 852 kg/ha, split into four equal doses: the first after thinning (four-leaf stage), followed by three doses at two-week intervals. Potassium was applied as potassium sulfate (48% K_2O) at 57 kg/ha in two equal doses, coinciding with the first and third nitrogen applications. Nitrogen and potassium fertilizers were delivered via fertigation.

Irrigation

Irrigation was performed using well water through a drip irrigation system with drippers delivering 4 L/h to maximize the wetted area and minimize water percolation beyond the root zone. Properties of irrigation water during both seasons are presented in Table 2.

Soil sampling and analysis

Soil samples were collected from the 0–20 cm layer at harvest, stored in polyethylene bags, air-dried, and sieved through a 2-mm mesh for chemical analysis. Soil pH was measured in a 1:2.5 soil-to-water suspension using a pH meter (Genway 3510, UK) (Sparks et al. 1996). Electrical conductivity (EC_e) was determined in a soil paste extract at 25 °C using an EC meter (Jenway 4310, UK) (Sparks et al. 1996). Soil organic matter was quantified using the Walkley–Black method (Sparks et al. 1996). Available nitrogen was extracted with 2 M KCl and measured via the Kjeldahl method (Sparks et al. 1996). Available phosphorus was extracted with 0.5 M $NaHCO_3$

Table 2 Some chemical properties of irrigation water used in 2021 and 2022 seasons

	pH	EC (dS/m)	Cations (meq/L)				Anions (meq/L)				SAR
			Ca^{2+}	Mg^{+2}	Na^{+}	K^{+}	CO_3^{2-}	HCO_3^{-}	Cl^{-}	SO_4^{2-}	
2021	7.98 ± 0.01	3.08 ± 0.02	10.05 ± 0.03	2.19 ± 0.02	18.09 ± 0.11	0.50 ± 0.01	0.02 ± 0	2.4 ± 0.01	19.87 ± 0.14	8.97 ± 0.08	7.31 ± 0.15
2022	7.85 ± 0.01	2.96 ± 0.02	9.66 ± 0.04	2.10 ± 0.02	17.39 ± 0.21	0.48 ± 0.01	0.01 ± 0	1.0 ± 0.02	19.09 ± 0.16	8.55 ± 0.09	7.17 ± 0.12

(Olsen et al. 1954) and measured spectrophotometrically (van Schouwenburg and Walinga 1967). Available potassium was extracted with 1 M NH_4OAc and quantified using a flame photometer (Sherwood Model 410, UK) (Jackson 1973). Available boron was determined as described by Keren and Bingham (Keren and Bingham 1958). Soil penetration resistance was measured using a handheld cone penetrometer (Gouda Geo-Equipment B.V., Hillegom, Netherlands) (Herrick and Jones 2002). Bulk density was determined from undisturbed soil cores, and total porosity was calculated from bulk and particle density (Richards 1954). Calcium carbonate content was quantified volumetrically using a Collins calcimeter (Cottenie 1980). Exchangeable sodium percentage (ESP) was calculated using the equation:

$$ESP = 1.95 + 1.03 \times SAR$$

where SAR (Sodium Adsorption Ratio) was calculated as follows:

$$SAR = \frac{[Na^+]}{\sqrt{\frac{[Ca^{2+}]+[Mg^{2+}]}{2}}}$$

where Na^+, Ca^{2+}, and Mg^{2+} were expressed in meq/L (Seilsepour et al. 2009).

These indicators were selected to assess core physical (e.g., bulk density for structure) and chemical (e.g., EC_e for salinity, nutrient availability for fertility) improvements relevant to saline sandy soils. However, comprehensive soil biological analyses—including microbial biomass carbon, enzyme activities related to nutrient cycling (e.g., dehydrogenase, urease, phosphatase), and microbial community structure— and CEC were not directly assessed in the present study. Although improvements in soil organic matter and nutrient retention suggest potential stimulation of biological activity and CEC (Canellas et al. 2015; Rudmin et al. 2019), future research integrating microbiological and biochemical indicators is necessary to elucidate the biological mechanisms underpinning the observed amendment-induced soil recovery and synergistic effects.

Plant sampling and biometric measurements

After 110 days from sowing, five plants were randomly sampled from the middle ridges of each sub-plot to measure biometric parameters. Leaf area was determined using the disk method, where ten 1-cm diameter disks were collected per plant, and leaf area index (LAI) was calculated following Watson (Watson 1958). Photosynthetic pigments (chlorophyll a, chlorophyll b, and carotenoids, in mg/g fresh weight) were quantified using a UV-160A spectrophotometer (Shimadzu, Kyoto, Japan) at absorbances of 663, 645, and 470 nm, respectively, as described by Lichtenthaler (Lichtenthaler 1987). The equations used were:

$$Chlorophylla = 12.12 \times A_{663} - 2.79 \times A_{647}$$

$$Chlorophyllb = 21.50 \times A_{647} - 5.10 \times A_{663}$$

$$Carotenoids = \left(1000 \times A_{470} - 1.82 \times Chla - 95.15 \times Chlb\right)/225$$

Photosynthesis rate was measured in the youngest fully expanded leaf at 110 days after sowing under a light intensity of 1000 µmol/m^2/s and 30 ± 2 °C using the LI-6400 portable photosynthesis system (Li-COR, Lincoln, NE, USA) (Tian-gen et al. 2017).

Yield and quality analysis

At harvest, ten guarded plants from the middle ridges of each sub-plot were sampled to measure root diameter (cm) and root and foliage fresh weights (g/plant). Root and foliage yields (ton/ha) were recorded from the entire plot. Sucrose percentage (Pol%) was determined in fresh root samples using the pol method (AOAC 2016) at the laboratory of Canal Sugar Plant, Minya–Malawi, Egypt. Root impurities (sodium, potassium, and α-amino-nitrogen, in meq/100 g beet) were analyzed, with sodium and potassium measured in digested beet solutions using a flame photometer and α-amino-nitrogen determined via hydrogenation (Cooke and Scott 1993). Sugar lost to molasses (SLM%) was calculated as SLM = 0.14 × (Na + K) + 0.25 × (α-amino N) + 0.5 (Hoffmann 2010). Extracted sugar percentage (ES%) was calculated as ES% = sucrose % − SLM% − 0.6 (Dexter et al. 1966). Quality index (QI) was determined as QI = (ES%/sucrose %) × 100 (Cooke and Scott 1993). Sugar yield (ton/ha) was calculated as sugar yield = root yield (ton/ha) × ES%. Field water use efficiency (FWUE) was calculated as FWUE = yield (kg/fed)/water applied (m^3/fed) (Michael 1978).

Statistical analysis

Data was analyzed using the Co-STATC software package with analysis of variance (ANOVA) for a split-plot design, following Gomez and Gomez (1984). Normality was tested prior to analysis. The Tukey's test was used to compare treatment means at a 5% probability level (Snedecor and Cochran 2014). Principal component analysis and Pearson's correlation were analyzed using OriginPro 10. All data are presented as mean ± standard error, and significance was declared at $P \leq 0.05$ unless otherwise stated.

To quantitatively evaluate treatment interactions, a synergy index (SI) was calculated for selected key parameters (LAI, root yield, sugar yield, and EC_e) using the following formula (Ianevski et al. 2022):

$$SI = (ObservedvalueofHG3800 - Expectedadditivevalue) / Expectedadditivevalue \times 100$$

where the expected additive value was calculated as:

$$Expectedadditivevalue = H0 + G0 + C3800 - 2 \times C0$$

This approach estimates whether the combined humic acid + glauconite + boron treatment (HG3800) exceeds the summed independent contributions of each component relative to the control. Positive SI values indicate synergistic effects, values near zero indicate additive responses, and negative values indicate antagonistic interactions.

Results

Impact of treatments on sugar beet growth and physiology

Leaf area index (LAI), a key measure of canopy development, varied significantly across treatments (Fig. 1A; $P \leq 0.05$). The HG3800 treatment yielded the highest values in both seasons (4.66 in 2021 and 4.43 in 2022), a 75% increase over the control (C0), which had the lowest (2.66 and 2.25, respectively). Treatments with 3800 g/ha boric acid generally surpassed lower doses and untreated plots, especially when paired with soil amendments. The LAI increased dose-dependently with boric acid from 0 to 1900 and 3800 g/ha within each amendment level. At equivalent boron rates, combined humic acid and glauconite (HG) outperformed single amendments. The synergy index for HG3800 confirmed positive interactions (+14% in 2021; +11% in 2022), enhancing canopy expansion under saline sandy conditions.

Chlorophyll a and b contents were also significantly affected (Figs. 1B and C). Humic acid combined with 1900 g/ha boric acid produced the highest chlorophyll a values in both seasons, while HG3800 consistently maximized chlorophyll b. Although individual amendments improved pigment concentration relative to the control, the ternary combination at 3800 g/ha demonstrated enhanced performance beyond most pairwise treatments, suggesting positive interaction effects under saline conditions.

Carotenoid content followed a similar trend (Fig. 1D), with HG3800 recording the highest values across both seasons. Treatments receiving 3800 g/ha boric acid generally showed greater carotenoid accumulation than lower doses, indicating improved stress tolerance and photoprotection.

Net photosynthetic rate was significantly enhanced by combined treatments (Fig. 1E). HG3800 achieved the highest photosynthetic activity in both years, markedly exceeding the control. While humic acid or glauconite alone improved photosynthesis compared with C0, the integrated HG3800 treatment resulted in the greatest enhancement, reflecting improved pigment content, nutrient availability, and stress mitigation.

Overall, the results demonstrate that growth and physiological responses were influenced not only by boron dose but also by its interaction with soil amendments, with the ternary combination at 3800 g/ha consistently producing superior performance.

Influence of treatments on sugar beet yield parameters

Root diameter and fresh weight, key indicators of root growth and yield potential, varied significantly across treatments (Fig. 2A; with significant humic × boron interactions, $P < 0.05$ per ANOVA). In 2021, HG3800 achieved the highest root diameter (10.8 cm) and fresh weight (1.25 kg/plant), followed by H1900 (10.2 cm, 1.15 kg/plant). In 2022, HG3800 again led (11.0 cm, 1.30 kg/plant), with H1900 close behind (10.4 cm, 1.20 kg/plant). Notably, H1900 outperformed H3800

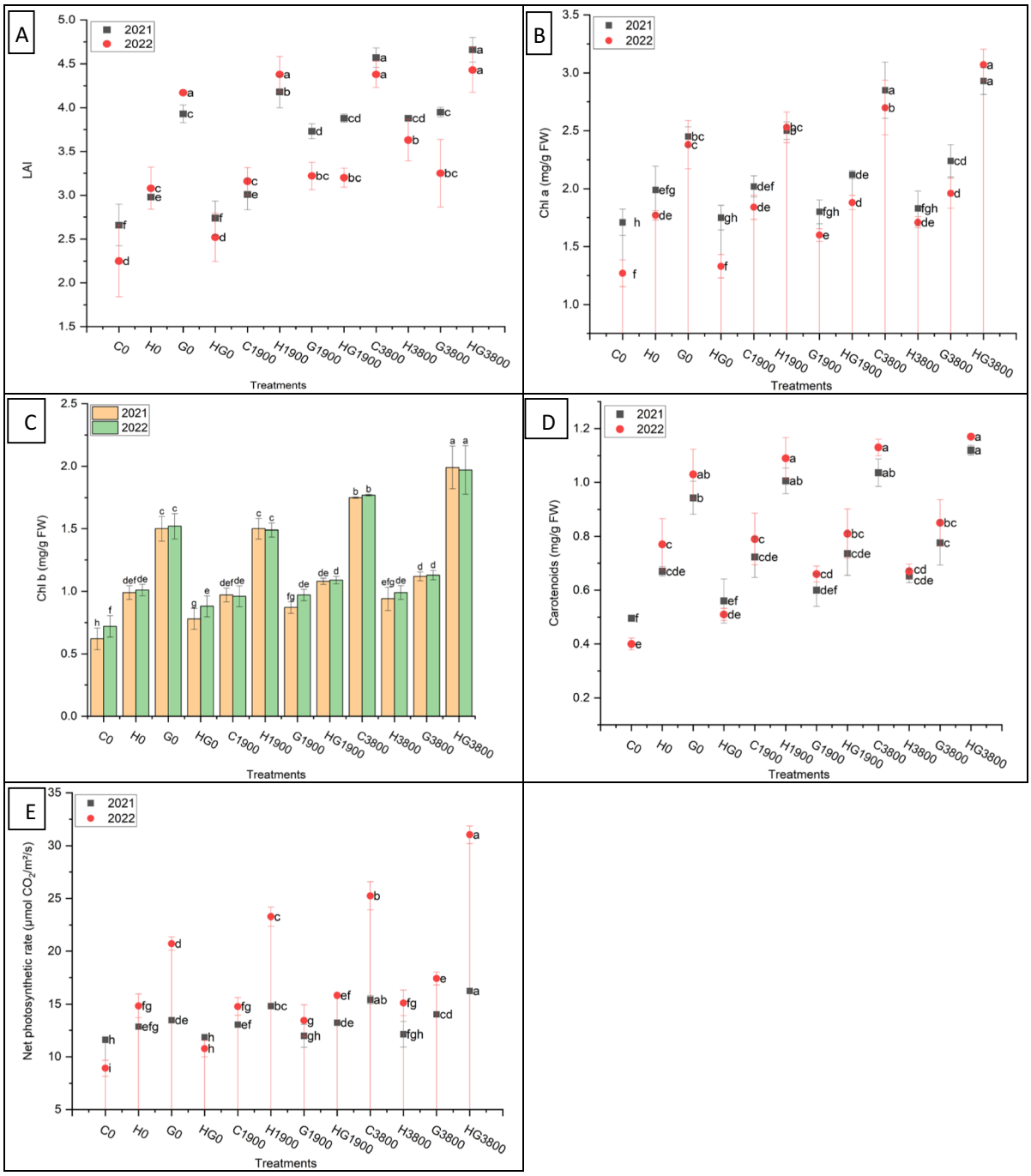


Fig. 1 Effects of soil amendments (humic acid and glauconite) and foliar boric acid application on: **A** leaf area index (LAI), **B** chlorophyll a, **C** chlorophyll b, **D** carotenoids, and **E** net photosynthetic rate of sugar beet grown in saline sandy soil during 2021 and 2022 seasons. Treatments include C0, H0, G0, HG0, C1900, H1900, G1900, HG1900, C3800, H3800, G3800, and HG3800. Different letters indicate significant differences at $P \leq 0.05$ (Tukey's test)

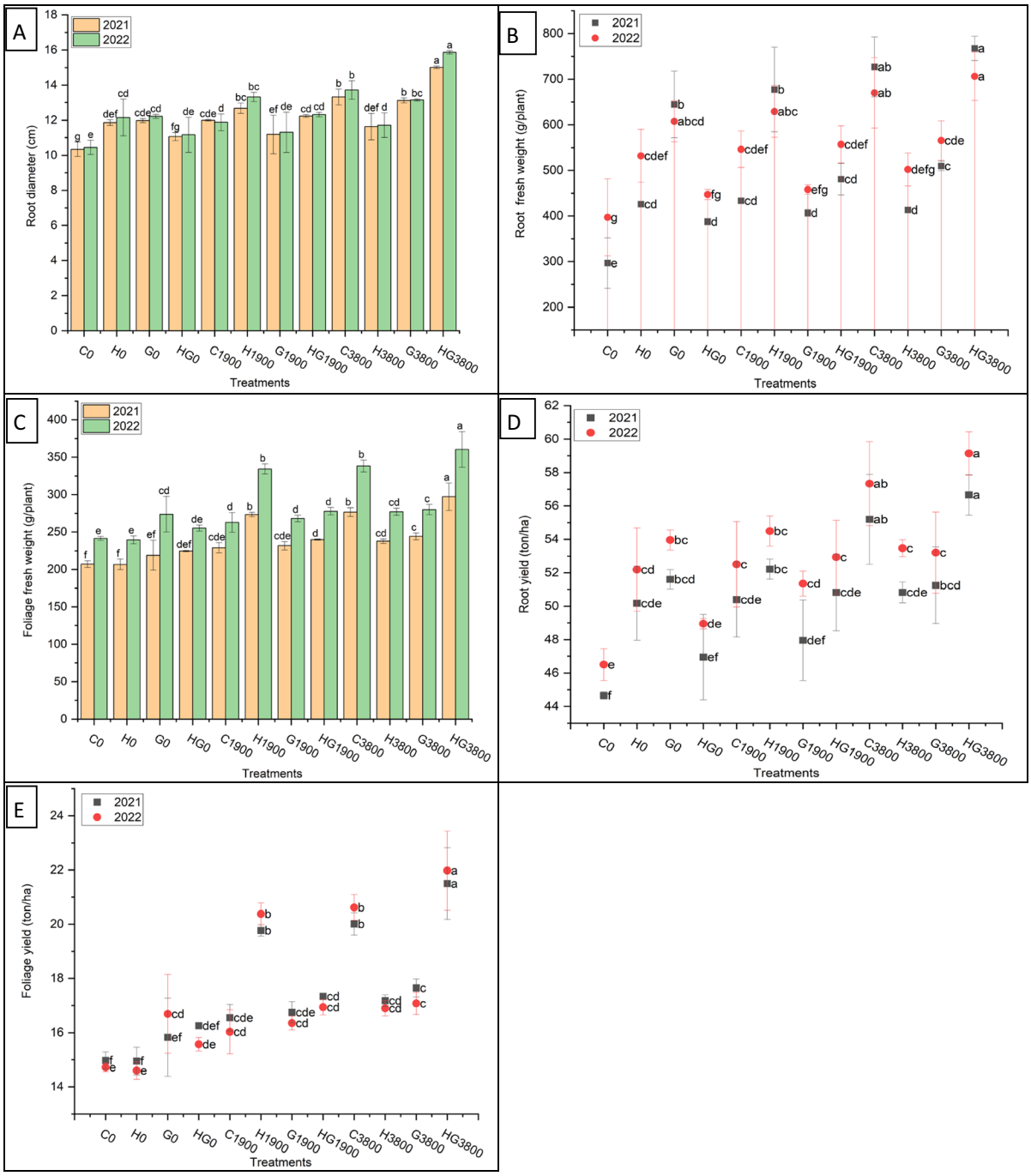


Fig. 2 Effects of soil amendments and foliar boric acid application on: **A** root diameter, **B** root fresh weight, **C** foliage fresh weight, **D** root yield, and **E** foliage yield of sugar beet during 2021 and 2022 seasons under saline sandy soil conditions. Treatments include C0, H0, G0, HG0, C1900, H1900, G1900, HG1900, C3800, H3800, G3800, and HG3800. Different letters indicate significant differences at $P \leq 0.05$ (Tukey's test)

(9.8 cm, 1.10 kg/plant in 2021; 10.0 cm, 1.12 kg/plant in 2022) in both metrics, reflecting a dose-dependent response where the lower boron dose (1900 g/ha) optimized cell wall formation and carbohydrate partitioning to roots under humic acid's stimulation, enhancing diameter and biomass accumulation. In contrast, the higher dose in H3800 (3800 g/ha) likely shifted resources toward sucrose translocation and stress mitigation (evident in higher sucrose content, Sect. 3.2), slightly reducing vegetative root growth in saline sandy soils. The control (C0) recorded the lowest values (8.5 cm, 0.90 kg/plant in 2021; 8.7 cm, 0.92 kg/plant in 2022), highlighting the amendments' role in improving root development.

Root fresh weight, a direct measure of root biomass, showed pronounced treatment effects (Fig. 2B). In 2021, HG3800 achieved the highest root fresh weight (768 g/plant), followed by C3800 (727 g/plant). In 2022, HG3800 remained the top performer (706 g/plant), with C3800 at 670 g/plant. The synergistic effect of humic acid, glauconite, and high boric acid in HG3800 significantly enhanced root biomass, likely due to improved soil structure and nutrient uptake. Humic acid treatments, particularly H1900 (677 g/plant in 2021; 629 g/plant in 2022), and glauconite treatments, such as G0 (645 g/plant in 2021; 608 g/plant in 2022), also significantly outperformed C0 (297 g/plant in 2021; 397 g/plant in 2022). The application of 3800 g/ha boric acid consistently amplified root fresh weight across treatments, highlighting its critical role in biomass accumulation under salinity stress.

Foliage fresh weight, indicative of above-ground biomass, was significantly influenced by the treatments (Fig. 2C). In 2021, HG3800 recorded the highest foliage fresh weight (297 g/plant), followed by C3800 (277 g/plant). In 2022, HG3800 again led with 360 g/plant, with C3800 at 338 g/plant. The HG3800 treatment consistently maximized foliage biomass, reflecting enhanced photosynthetic capacity and nutrient assimilation facilitated by the combined amendments. Humic acid treatments, such as H1900 (273 g/plant in 2021; 334 g/plant in 2022), and glauconite treatments, like G0 (219 g/plant in 2021; 274 g/plant in 2022), also significantly increased foliage fresh weight compared to C0 (207 g/plant in 2021; 241 g/plant in 2022). The dose-dependent effect of boric acid was clear, with 3800 g/ha treatments generally outperforming lower doses, emphasizing its role in promoting vegetative growth in saline soils.

Root yield showed a clear dose-dependent increase with higher boric acid application rates across all amendment categories (Fig. 2D). Treatments at 3800 g/ha consistently outperformed those at 1900 g/ha within each category. At the same boron level, the combined humic acid and glauconite treatment (HG) produced higher yields than either amendment alone, indicating a synergistic benefit from their interaction. The HG3800 treatment achieved the highest root yields in both years—56.7 ton/ha in 2021 and 59.1 ton/ha in 2022—surpassing the control with high boron (C3800) at 55.2 ton/ha and 57.3 ton/ha, respectively. This superior performance in HG3800 stems from the elevated boron dose combined with enhanced root development, nutrient uptake, soil structure improvements, and stress mitigation provided by the humic acid–glauconite combination. Synergistic effects were evident, with a synergy index of + 15% in 2021 and + 13% in 2022 for root yield, meaning the ternary combination exceeded the expected additive response. Individual amendment treatments also significantly boosted yields compared to the untreated control (C0: 44.7 ton/ha in 2021; 46.5 ton/ha in 2022). For example, humic acid alone (H1900) reached 52.2 ton/ha (2021) and 54.5 ton/ha (2022), while glauconite alone (G0) achieved 51.6 ton/ha (2021) and 54.0 ton/ha (2022). These gains surpassed predictions from additive effects of the components (e.g., mean expected ~ 49.3 ton/ha in 2021), yielding an approximate 15% synergistic improvement. Overall, higher boric acid rates (3800 g/ha) reliably enhanced root yield in saline sandy soils, underscoring boron's role in improving productivity, particularly when paired with these soil amendments.

Foliage yield, reflecting above-ground productivity, was significantly enhanced by the treatments (Fig. 2E). In 2021, HG3800 recorded the highest foliage yield (21.5 ton/ha), followed by C3800 (20.0 ton/ha). In 2022, HG3800 again led with 22.0 ton/ha, with C3800 at 20.6 ton/ha. The HG3800 treatment consistently maximized foliage yield, likely due to improved foliage biomass and photosynthetic efficiency under salinity stress. Humic acid treatments, particularly H1900 (19.8 ton/ha in 2021; 20.4 ton/ha in 2022), and glauconite treatments, such as G3800 (17.7 ton/ha in 2021; 17.1 ton/ha in 2022), also

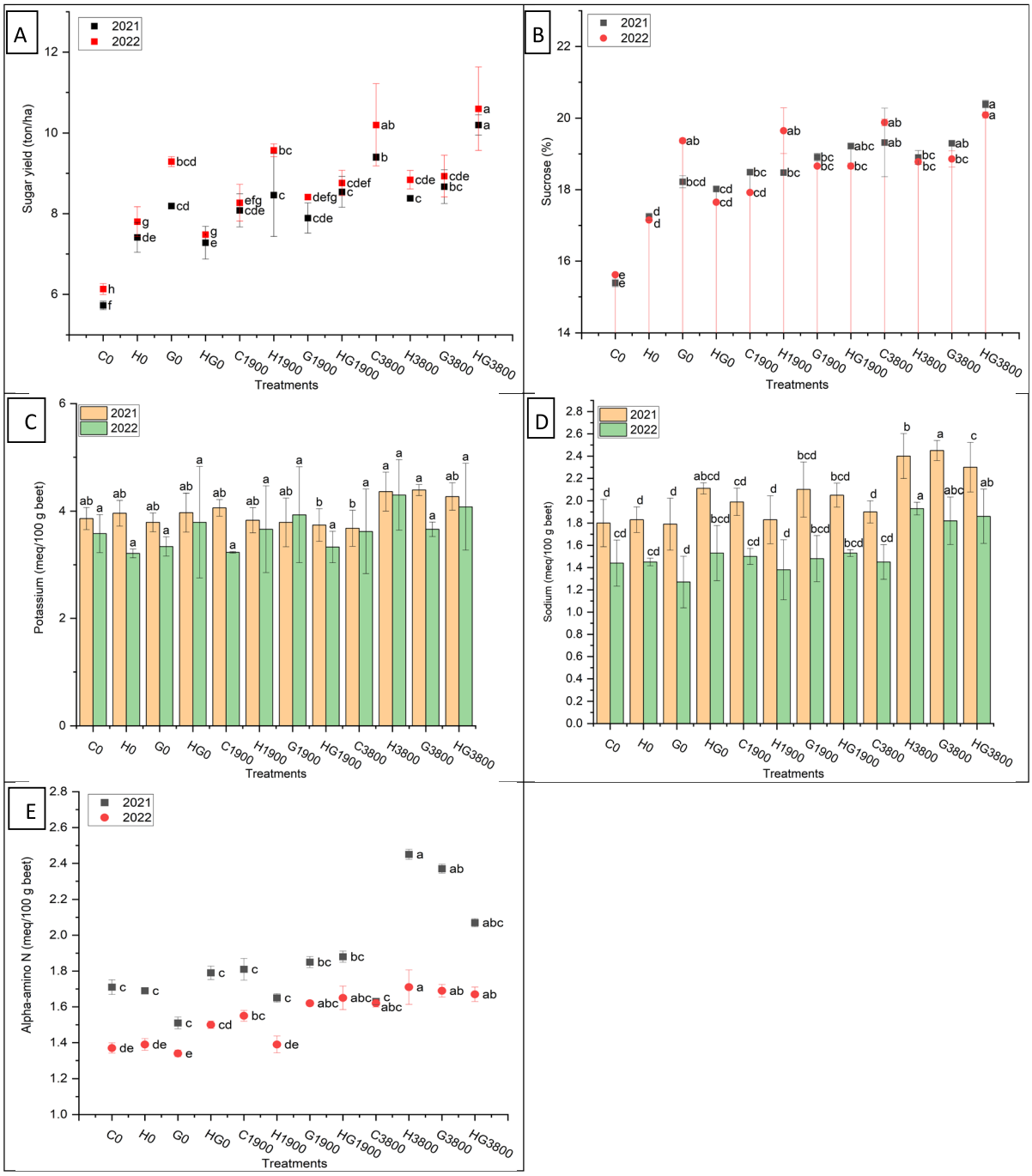


Fig. 3 Effects of soil amendments and foliar boric acid application on: **A** sugar yield, **B** sucrose percentage, **C** potassium (K), **D** sodium (Na), and **E** α-amino nitrogen in sugar beet roots during 2021 and 2022 seasons. Treatments include C0, H0, G0, HG0, C1900, H1900, G1900, HG1900, C3800, H3800, G3800, and HG3800. Different letters indicate significant differences at $P \leq 0.05$ (Tukey's test)

significantly outperformed C0 (15.0 ton/ha in 2022; 14.7 ton/ha in 2021).

Treatment effects on sugar yield and quality of sugar beet in saline sandy soil

Sugar yield was significantly affected by treatment (Fig. 3A), showing a clear dose-dependent response to boric acid application across all amendment categories. The 3800 g/ha rate consistently produced higher sugar yields than 1900 g/ha within each amendment level. At equivalent boron doses, the combined humic acid and glauconite treatment (HG) outperformed individual amendments, highlighting a positive synergistic interaction. HG3800 delivered the highest sugar yields—10.2 ton/ha in 2021 and 11.5 ton/ha in 2022—representing a 79% increase over the untreated control, which recorded the lowest values in both years. This superior performance in HG3800 arose from the combined benefits of elevated boron availability and enhanced soil conditions provided by the integrated amendments. Synergistic effects were pronounced, with a synergy index of + 32% in 2021 and + 29% in 2022 for sugar yield, indicating that the ternary combination substantially exceeded the expected additive contributions of the individual components. Treatments pairing soil amendments with the higher boric acid rate (3800 g/ha) reliably surpassed lower-dose and control treatments in both seasons. Despite the overall superiority of the HG3800 treatment, not all combinations exhibited consistent synergistic responses. For instance, glauconite alone (G0) outperformed G1900 and G3800 in sugar yield during the first season, suggesting that boron supplementation did not universally enhance potassium-mediated sucrose accumulation. Similarly, H1900 exceeded H3800 in root diameter and fresh weight, indicating that higher boron doses may have shifted assimilate allocation toward stress mitigation and sucrose stabilization rather than vegetative biomass expansion. In addition, elevated impurity levels observed in H3800 and HG3800 treatments demonstrate that enhanced sucrose concentration does not always coincide with improved technological quality. These findings indicate that treatment interactions were dose-dependent and context-specific rather than universally synergistic, underscoring the importance of cautious interpretation of combined amendment effects.

Sucrose content, a critical determinant of sugar beet quality, varied significantly across treatments (Fig. 3B). In 2021, sucrose percentages ranged from 15.4% (C0) to 20.4% (HG3800), while in 2022, the range extended from 15.6% (C0) to 20.1% (HG3800). Glauconite-based treatments (G0, G1900, G3800) consistently outperformed humic acid treatments, with G0 achieving 18.2% and 19.4% in 2021 and 2022, respectively. The HG combination, particularly with 3800 g/ha boric acid, maximized sucrose accumulation, reflecting enhanced photosynthetic efficiency and assimilate partitioning. Boric acid's role in sucrose enhancement was evident, as higher doses correlated with increased sucrose percentages, likely due to its influence on carbohydrate metabolism and membrane stability under saline stress.

Impurity levels, measured as meq/100 g beet, significantly influenced sugar beet processability. Potassium levels were lowest in C0 (3.86 in 2021, 3.58 in 2022) and highest in H3800 (4.36 in 2021) and HG3800 (4.08 in 2022) (Fig. 3C). Sodium followed a similar trend, with C0 recording 1.71 and 1.37 in 2021 and 2022 (Fig. 3D), respectively, while HG3800 reached 2.07 and 1.67. α-amino N was notably high in H3800 (1.83 in 2021, 1.64 in 2022) and lowest in C3800 (1.66 in 2021, 1.42 in 2022) (Fig. 3E). Glauconite treatments generally reduced impurity levels compared to humic acid, potentially due to improved CEC and reduced sodium uptake. Boric acid at 3800 g/ha increased impurities in some cases (e.g., H3800, HG3800), possibly due to altered nutrient dynamics, but these levels remained within acceptable ranges for processing.

Sugar lost to molasses, an indicator of processing efficiency, was minimized in treatments with glauconite and higher boric acid doses (Fig. 4A). In 2021, losses ranged from 1.79% (G0) to 2.45% (G3800), while in 2022, they ranged from 1.27% (G0) to 1.93% (H3800). The G0 treatment consistently achieved the lowest losses, underscoring glauconite's role in reducing non-sucrose compounds that hinder crystallization. Boric acid at 3800 g/ha reduced losses in C3800 (1.45% in 2022) and HG3800 (1.86% in 2022) compared to lower doses, suggesting improved sugar recovery. Humic acid treatments, particularly H3800, exhibited higher losses, indicating a potential limitation in their ability to mitigate impurity impacts during processing.

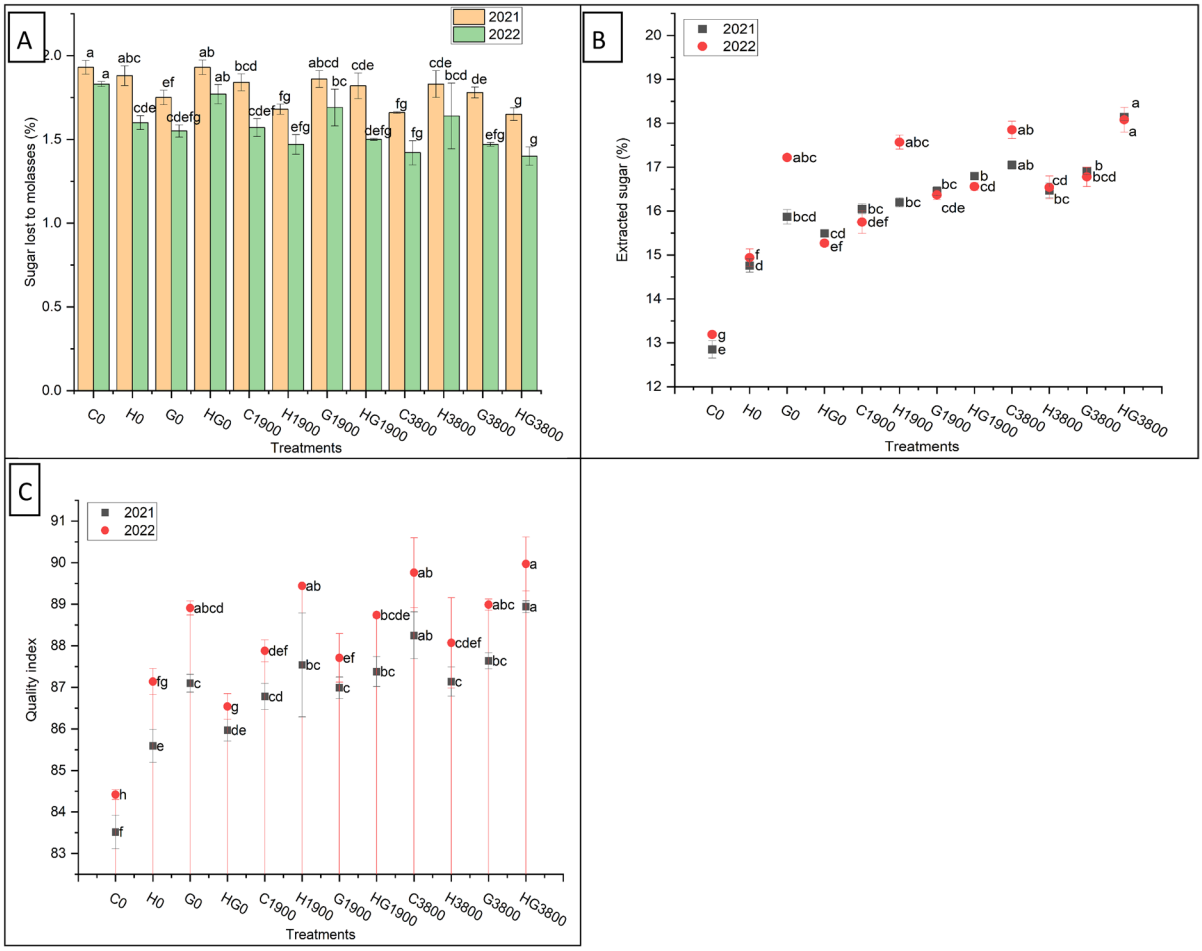


Fig. 4 Effects of soil amendments and foliar boric acid application on: **A** sugar lost to molasses, **B** extracted sugar percentage, and **C** quality index of sugar beet during 2021 and 2022 seasons. Treatments include C0, H0, G0, HG0, C1900, H1900, G1900, HG1900, C3800, H3800, G3800, and HG3800. Different letters indicate significant differences at $P \leq 0.05$ (Tukey's test)

Extracted sugar percentages, reflecting the proportion of sucrose successfully recovered, were highest in HG3800 (88.9% in 2021, 90.0% in 2022) and lowest in C0 (83.5% in 2021, 84.4% in 2022) (Fig. 4B). Glauconite-based treatments (G0, G1900, G3800) consistently outperformed humic acid treatments, with G0 achieving 87.1% and 88.9% in 2021 and 2022, respectively. The addition of boric acid, especially at 3800 g/ha, enhanced extraction efficiency across all amendments, with HG3800 demonstrating the most significant gains. This suggests that the combined effects of humic acid, glauconite, and boric acid optimize sucrose crystallization by reducing impurities and improving juice purity.

The quality index, a composite measure of sugar beet quality, was highest in HG3800 (18.14 in 2021, 18.08 in 2022) and lowest in C0 (12.85 in 2021, 13.19 in 2022) (Fig. 4C). Glauconite treatments (G0, G1900, G3800) consistently improved the quality index compared to humic acid treatments, with G0 achieving 15.87 and 17.22 in 2021 and 2022, respectively. Boric acid application, particularly at 3800 g/ha, significantly enhanced the quality index across all treatments, reflecting improved sucrose content and reduced impurities. The synergistic effect of HG with 3800 g/ha boric acid underscores the potential of combined

Table 3 Variations in soil chemical properties after foliar application of boric acid (B) and soil amendments (humic acid (HA) and glauconite (GL)) to sugar beet (*Beta vulgaris* L., var. Avantage) grown in saline sandy soil during two successive seasons (2021–2022)

	EC_e (dS/m)		pH		SOM (%)		$CaCO_3$ (%)		ESP (%)	
Treatments	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022
Main plot										
CK	6.14 ± 0.01a	5.75 ± 0.02a	7.76 ± 0.02a	7.76 ± 0.05a	0.76 ± 0.01b	0.83 ± 0.02b	12.7 ± 0.02a	13.0 ± 0.06a	1.98 ± 0.2a	1.87 ± 0.1a
HA	5.28 ± 0.01b	5.27 ± 0.02b	7.71 ± 0.03ab	7.71 ± 0.04b	0.78 ± 0.01b	0.86 ± 0.01a	7.6 ± 0.01c	7.9 ± 0.05c	1.75 ± 0.2b	1.74 ± 0.0b
GL	5.25 ± 0.02c	5.24 ± 0.02c	7.68 ± 0.04b	7.68 ± 0.04b	0.79 ± 0.00b	0.86 ± 0.01a	7.8 ± 0.02b	8.0 ± 0.08b	1.74 ± 0.2c	1.74 ± 0.1c
HA + GL	4.65 ± 0.02d	4.62 ± 0.03d	7.51 ± 0.03c	7.48 ± 0.03c	0.84 ± 0.01a	0.88 ± 0.02a	7.3 ± 0.01d	7.6 ± 0.08d	1.56 ± 0.1d	1.56 ± 0.1d
Sub-plot										
B0	5.33 ± 0.00a	5.22 ± 0.02a	7.67 ± 0.04a	7.66 ± 0.04a	0.79 ± 0.01a	0.85 ± 0.02a	9.0 ± 0.01a	9.3 ± 0.09a	1.76 ± 0.2a	1.73 ± 0.2a
B1900	5.33 ± 0.01a	5.22 ± 0.02a	7.67 ± 0.03a	7.66 ± 0.02a	0.79 ± 0.01a	0.86 ± 0.01a	8.8 ± 0.01b	9.0 ± 0.09b	1.76 ± 0.0a	1.73 ± 0.1a
B3800	5.33 ± 0.01a	5.22 ± 0.01a	7.66 ± 0.04a	7.65 ± 0.03a	0.80 ± 0.00a	0.86 ± 0.01a	8.9 ± 0.02ab	9.1 ± 0.10ab	1.76 ± 0.1a	1.73 ± 0.1a
Interaction										
C0	6.14 ± 0.03a	5.75 ± 0.00a	7.76 ± 0.04a	7.75 ± 0.04a	0.76 ± 0.00bc	0.83 ± 0.01d	12.8 ± 0.17a	13.0 ± 0.08a	1.98 ± 0.1a	1.87 ± 0.0a
H0	6.14 ± 0.01a	5.74 ± 0.01a	7.76 ± 0.04ab	7.76 ± 0.01a	0.76 ± 0.00c	0.82 ± 0.01d	12.6 ± 0.06a	13.0 ± 0.09a	1.98 ± 0.0a	1.87 ± 0.0a
G0	6.14 ± 0.01a	5.76 ± 0.01a	7.77 ± 0.04a	7.75 ± 0.00a	0.76 ± 0.00bc	0.83 ± 0.02d	12.7 ± 0.12a	13.0 ± 0.10a	1.97 ± 0.0a	1.88 ± 0.0a
HG0	5.29 ± 0.00b	5.27 ± 0.00b	7.71 ± 0.00c	7.71 ± 0.01b	0.78 ± 0.02bc	0.86 ± 0.00c	7.6 ± 0.05bcd	8.0 ± 0.25bc	1.75 ± 0.0b	1.74 ± 0.0b
C1900	5.29 ± 0.00b	5.27 ± 0.01b	7.72 ± 0.00abc	7.7 ± 0.01bc	0.79 ± 0.01b	0.86 ± 0.01bc	7.6 ± 0.02bcd	7.7 ± 0.02bc	1.75 ± 0.0b	1.74 ± 0.0b
H1900	5.28 ± 0.00bc	5.26 ± 0.01b	7.71 ± 0.02bc	7.71 ± 0.00bc	0.79 ± 0.02bc	0.86 ± 0.02c	7.6 ± 0.40bcd	7.9 ± 0.24bc	1.75 ± 0.0bc	1.74 ± 0.0b
G1900	5.25 ± 0.03d	5.24 ± 0.00 cd	7.70 ± 0.04c	7.69 ± 0.00bc	0.77 ± 0.03bc	0.86 ± 0.02c	8.0 ± 0.31b	8.3 ± 0.47b	1.74 ± 0.1d	1.73 ± 0.0c
HG1900	5.26 ± 0.00 cd	5.25 ± 0.00c	7.68 ± 0.05c	7.68 ± 0.01c	0.79 ± 0.02bc	0.86 ± 0.01c	7.6 ± 0.04bcd	7.8 ± 0.01bc	1.74 ± 0.0 cd	1.74 ± 0.0c
C3800	5.25 ± 0.01 cd	5.23 ± 0.01d	7.68 ± 0.05c	7.68 ± 0.03c	0.78 ± 0.02bc	0.86 ± 0.0c	7.8 ± 0.28bc	8.0 ± 0.43b	1.74 ± 0.0 cd	1.73 ± 0.0c
H3800	4.65 ± 0.01e	4.62 ± 0.01e	7.51 ± 0.01d	7.49 ± 0.03d	0.84 ± 0.03a	0.88 ± 0.01abc	7.5 ± 0.33cde	7.9 ± 0.50bc	1.57 ± 0.0e	1.56 ± 0.0d
G3800	4.65 ± 0.00e	4.62 ± 0.00e	7.51 ± 0.00d	7.49 ± 0.00d	0.85 ± 0.02a	0.89 ± 0.00a	7.1 ± 0.01e	7.3 ± 0.01c	1.56 ± 0.0e	1.56 ± 0.0d
HG3800	4.65 ± 0.00e	4.62 ± 0.00e	7.50 ± 0.04d	7.48 ± 0.00d	0.84 ± 0.03a	0.88 ± 0.01ab	7.3 ± 0.32de	7.6 ± 0.50bc	1.56 ± 0.0e	1.56 ± 0.0d
F-test										
Main plot	**	**	**	**	**	*	**	**	**	**
Sub-plot	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Interaction	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

amendments to maximize sugar beet quality under saline conditions.

Treatment effects on soil chemical properties

In 2021, EC_e values ranged from 4.65 dS/m in treatments with 3800 g/ha boric acid (H3800, G3800, HG3800) to 6.14 dS/m in treatments without boric acid (C0, H0, G0) (Table 3). By 2022, EC_e slightly decreased across most treatments, with the lowest values again observed in H3800, G3800, and HG3800 (4.62 dS/m) and the highest in G0 (5.76 dS/m). The application of 3800 g/ha boric acid consistently reduced EC_e compared to 1900 g/ha and control treatments, suggesting enhanced leaching of salts. The HG combination, particularly at higher boric acid levels, showed lower EC_e values compared with individual amendments. However, because the interaction effect between main plot and sub-plot factors was not statistically significant (Table 3), these reductions should be interpreted as the result of additive main effects rather than confirmed synergistic interactions. The synergy index for EC_e reduction was − 17% in 2021 and − 15% in 2022 (negative values indicating enhanced reduction relative to additive expectations), confirming a synergistic salinity mitigation effect.

Soil pH values in 2021 ranged from 7.50 (HG3800) to 7.77 (G0), with a slight decrease in 2022 (7.48 for HG3800 to 7.76 for H0). Treatments with 3800 g/ha boric acid (H3800, G3800, HG3800) significantly lowered pH compared to controls and lower boric acid doses, with reductions of up to 0.27 units in 2021 and 0.28 units in 2022 relative to C0. The HG combination showed a pronounced effect, particularly in HG3800, which consistently recorded the lowest pH. This acidification is likely attributable to the release of organic acids from humic acid and the cation exchange capacity of glauconite, which together enhance proton activity in the soil solution. These findings suggest that high boric acid doses, especially with HG, can counteract the alkalinity typical of saline soils, creating a more favorable environment for sugar beet growth.

The SOM percentages were relatively stable across treatments, ranging from 0.46% (C0, H0, G0 in 2021) to 0.55% (G3800 in 2022). Treatments with 3800 g/ha boric acid (H3800, G3800, HG3800) exhibited the highest SOM in both years, with increases of up to 0.09% compared to controls. The HG combination, particularly HG3800, showed a modest but consistent SOM increase (0.54% in 2021, 0.58% in 2022), reflecting the contribution of humic acid to organic carbon content. Glauconite alone (G3800) also enhanced SOM, likely due to its ability to stabilize organic matter through cation bridging. These results underscore the role of high boric acid doses and HG in improving soil fertility by enhancing organic matter retention, which is critical for nutrient availability in saline sandy soils.

$CaCO_3$ content varied from 1.56% (G3800, HG3800 in 2021 and 2022) to 1.98% (C0, H0 in 2021). Treatments with 3800 g/ha boric acid significantly reduced $CaCO_3$ compared to controls, with H3800, G3800, and HG3800 showing reductions of up to 0.42% in 2021 and 0.31% in 2022 relative to C0. The HG combination was particularly effective, with HG3800 consistently exhibiting the lowest $CaCO_3$ levels. This reduction likely results from the solubilization of calcium by humic acid and the enhanced cation exchange facilitated by glauconite, which may precipitate calcium in less stable forms. Lower $CaCO_3$ content in these treatments suggests improved soil structure and reduced alkalinity, benefiting sugar beet root development.

The ESP values decreased significantly with increasing boric acid levels, ranging from 7.1% (G3800 in 2021) to 12.8% (C0 in 2021). In 2022, ESP ranged from 7.3% (G3800) to 13.0% (C0, H0, G0). The 3800 g/ha boric acid treatments (H3800, G3800, HG3800) reduced ESP by up to 5.7% in 2021 and 5.7% in 2022 compared to C0, with G3800 showing the lowest ESP overall. The HG combination, particularly HG3800, maintained low ESP values. Since interaction effects were not statistically significant (Table 3), this improvement reflects strong main effects of the amendments rather than statistically verified synergism. This reduction in ESP is likely due to the combined effects of humic acid's chelating properties and glauconite's high cation exchange capacity, which replace sodium with calcium and magnesium ions. These findings highlight the efficacy of high boric acid doses and HG in alleviating sodicity, thereby improving soil physical properties and nutrient uptake for sugar beets.

Treatments are: C0 (control + 0 boric acid), H0 (humic acid + 0 boric acid), G0 (glauconite + 0 boric acid), HG0 (humic acid + glauconite + 0 boric acid), C1900 (control + 1900 boric acid), H1900 (humic

acid + 1900 boric acid), G1900 (glauconite + 1900 boric acid), HG1900 (humic acid + glauconite + 1900 boric acid), C3800 (control + 3800 boric acid), H3800 (humic acid + 3800 boric acid), G3800 (glauconite + 3800 boric acid), and HG3800 (humic acid + glauconite + 3800 boric acid). Different letters above columns are significant at level of $p \leq 0.05$ according to the Tukey's test.

Soil nutrient availability in response to soil amendments and boric acid

In 2021, available N ranged from 22.6 mg/kg in control (C0) to 32.8 mg/kg in G3800, with a similar trend in 2022 (23.7 mg/kg in C0 to 33.2 mg/kg in G3800) (Table 4). Treatments with 3800 g/ha boric acid consistently exhibited the highest N availability, with G3800, HG3800, and H3800 increasing N by up to 45.1% in 2021 and 40.1% in 2022 compared to C0. The HG combination, particularly HG3800, enhanced N availability (30.0 mg/kg in 2021, 30.3 mg/kg in 2022), surpassing the control by approximately 33%. Humic acid and glauconite individually contributed to N retention, likely through improved organic matter stabilization and cation exchange, respectively. The pronounced effect of G3800 suggests that glauconite's high cation exchange capacity facilitates ammonium retention, while high boric acid doses may enhance microbial activity, further boosting N mineralization.

Table 4 Variations in soil available nutrients (mg/kg) after foliar application of boric acid (B) and soil amendments (humic acid (HA) and glauconite (GL)) to sugar beet (*Beta vulgaris* L., var. Avantage) grown in saline sandy soil during two successive seasons (2021–2022)

	Nitrogen		Phosphorus		Potassium		Boron	
Treatments	2021	2022	2021	2022	2021	2022	2021	2022
Main plot								
CK	23.28 ± 0.17c	24.94 ± 0.11b	7.31 ± 0.02c	7.64 ± 0.01d	164 ± 4d	163 ± 3d	0.15 ± 0.04c	0.14 ± 0.01c
HA	26.21 ± 0.11b	26.41 ± 0.13b	7.64 ± 0.05b	7.97 ± 0.03c	175 ± 4c	165 ± 5c	0.17 ± 0.03b	0.18 ± 0.04b
GL	25.39 ± 0.22bc	25.62 ± 0.16b	7.64 ± 0.03b	8.05 ± 0.03b	184 ± 5b	172 ± 3b	0.18 ± 0.02b	0.18 ± 0.02b
HA + GL	30.72 ± 0.21a	31.03 ± 0.14a	7.95 ± 0.04a	8.18 ± 0.04a	195 ± 7a	182 ± 5a	0.22 ± 0.01a	0.23 ± 0.01a
Sub-plot								
B0	25.64 ± 0.18a	26.07 ± 0.11a	7.63 ± 0.04a	7.96 ± 0.01a	179 ± 8a	171 ± 6a	0.16 ± 0.02a	0.16 ± 0.00a
B1900	26.84 ± 0.18a	27.54 ± 0.21a	7.63 ± 0.03a	7.96 ± 0.02a	179 ± 9a	170 ± 5a	0.19 ± 0.03a	0.19 ± 0.01a
B3800	26.72 ± 0.22a	27.38 ± 0.12a	7.63 ± 0.02a	7.96 ± 0.03a	179 ± 4a	170 ± 4a	0.19 ± 0.01a	0.20 ± 0.02a
Interaction								
C0	22.60 ± 0.62b	23.65 ± 0.95a	7.32 ± 0.01c	7.64 ± 0.01e	163 ± 9d	163 ± 7d	0.16 ± 0.00b	0.14 ± 0.02c
H0	23.63 ± 0.01ab	25.45 ± 0.01a	7.31 ± 0.00c	7.64 ± 0.00e	164 ± 8d	162 ± 8e	0.16 ± 0.00b	0.15 ± 0.00bc
G0	23.62 ± 0.04ab	25.71 ± 0.77a	7.31 ± 0.01c	7.65 ± 0.01d	163 ± 3d	163 ± 9de	0.15 ± 0.01b	0.14 ± 0.01bc
HG0	25.64 ± 0.01ab	26.05 ± 0.04a	7.64 ± 0.01b	7.97 ± 0.00c	175 ± 5c	165 ± 4c	0.15 ± 0.03b	0.16 ± 0.03bc
C1900	26.00 ± 0.58ab	26.25 ± 0.01a	7.64 ± 0.00b	7.97 ± 0.00c	175 ± 6c	165 ± 9c	0.17 ± 0.03ab	0.18 ± 0.04abc
H1900	27.01 ± 0.30ab	26.92 ± 0.01a	7.64 ± 0.00b	7.98 ± 0.00c	175 ± 6c	165 ± 6c	0.20 ± 0.01ab	0.21 ± 0.01abc
G1900	24.93 ± 0.12ab	25.01 ± 0.14a	7.64 ± 0.01b	8.06 ± 0.01b	184 ± 7b	172 ± 8b	0.16 ± 0.04b	0.16 ± 0.04bc
HG1900	24.96 ± 0.01ab	25.28 ± 0.46a	7.64 ± 0.00b	8.05 ± 0.00b	183 ± 9b	172 ± 9b	0.18 ± 0.04ab	0.18 ± 0.04abc
C3800	26.29 ± 0.34ab	26.58 ± 0.01a	7.64 ± 0.00b	8.05 ± 0.01b	184 ± 3b	172 ± 3b	0.21 ± 0.01ab	0.21 ± 0.01abc
H3800	29.38 ± 0.77ab	29.58 ± 0.27a	7.95 ± 0.00a	8.18 ± 0.00a	194 ± 5a	182 ± 3a	0.18 ± 0.08ab	0.19 ± 0.07abc
G3800	32.79 ± 0.54a	33.20 ± 0.55a	7.95 ± 0.00a	8.18 ± 0.00a	194 ± 6a	182 ± 6a	0.26 ± 0.01a	0.27 ± 0.01a
HG3800	29.980.77 ± ab	30.30 ± 0.78a	7.95 ± 0.00a	8.18 ± 0.01a	195 ± 9a	182 ± 9a	0.22 ± 0.07ab	0.23 ± 0.07ab
F-test								
Main plot	**	**	**	**	**	**	**	**
Sub-plot	ns	ns	ns	ns	ns	ns	ns	ns
Interaction	ns	ns	ns	ns	ns	ns	ns	ns

Phosphorus availability ranged from 7.31 mg/kg (H0, G0 in 2021) to 7.95 mg/kg (H3800, G3800, HG3800 in 2021), with 2022 values slightly higher (7.64 mg/kg in C0, H0, G0 to 8.18 mg/kg in H3800, G3800, HG3800). Treatments with 3800 g/ha boric acid significantly increased P availability, with H3800, G3800, and HG3800 showing increases of up to 8.8% in 2021 and 7.1% in 2022 compared to C0. The HG combination (HG3800) consistently improved P levels (7.95 mg/kg in 2021, 8.18 mg/kg in 2022), reflecting synergistic effects of humic acid's chelating properties and glauconite's ability to reduce P fixation in saline soils. The enhanced P availability in these treatments likely results from the acidification induced by high boric acid doses, which increases P solubility, and the organic complexes formed by humic acid, which prevent P precipitation.

Potassium availability varied from 163 mg/kg (C0, G0 in 2021) to 195 mg/kg (HG3800 in 2021), with 2022 values ranging from 162 mg/kg (H0) to 182 mg/kg (H3800, G3800, HG3800). The 3800 g/ha boric acid treatments significantly enhanced K availability, with HG3800, H3800, and G3800 increasing K by up to 19.6% in 2021 and 11.7% in 2022 compared to C0. The HG combination was particularly effective, with HG3800 achieving the highest K levels in 2021 (195 mg/kg). Glauconite's natural K content and high cation exchange capacity likely contributed to K retention, while humic acid enhanced K solubility through organic matter interactions. The consistent K increase in high boric acid treatments suggests that these amendments mitigate K leaching in saline sandy soils, ensuring greater availability for sugar beet uptake.

Boron availability ranged from 0.15 mg/kg (G0, HG0 in 2021) to 0.26 mg/kg (G3800 in 2021), with 2022 values from 0.14 mg/kg (C0, G0) to 0.27 mg/kg (G3800). Treatments with 3800 g/ha boric acid markedly increased B availability, with G3800, HG3800, and C3800 showing increases of up to 73.3% in 2021 and 92.9% in 2022 compared to C0. The HG combination (HG3800) enhanced B levels (0.22 mg/kg in 2021, 0.23 mg/kg in 2022), surpassing controls by approximately 50%. Glauconite's role in B retention, combined with direct B inputs from boric acid, drove these increases, while humic acid likely stabilized B in the soil solution. The pronounced B availability in G3800 underscores glauconite's efficacy in sustaining B levels, critical for sugar beet quality and yield under saline conditions.

Treatments are: C0 (control + 0 boric acid), H0 (humic acid + 0 boric acid), G0 (glauconite + 0 boric acid), HG0 (humic acid + glauconite + 0 boric acid), C1900 (control + 1900 boric acid), H1900 (humic acid + 1900 boric acid), G1900 (glauconite + 1900 boric acid), HG1900 (humic acid + glauconite + 1900 boric acid), C3800 (control + 3800 boric acid), H3800 (humic acid + 3800 boric acid), G3800 (glauconite + 3800 boric acid), and HG3800 (humic acid + glauconite + 3800 boric acid). Different letters above columns are significant at level of $p \leq 0.05$ according to the Tukey's test.

Impact of amendments on soil physical parameters

Bulk density (g/cm^3), a critical indicator of soil compaction, exhibited a consistent reduction across treatments with increasing boric acid application and the inclusion of humic acid and glauconite (Table 5). In 2021, the control treatment (C0) recorded a bulk density of 1.66, which remained relatively stable at 1.65 in 2022. Single amendments (H0, G0) showed marginal improvements, maintaining bulk densities at 1.65 in both years. However, the combination of humic acid and glauconite (HG0) slightly reduced bulk density to 1.64 in 2021 and 1.63 in 2022, suggesting a synergistic effect of organic and mineral amendments in enhancing soil structure. The addition of boric acid further amplified this trend. At 1900 g/ha, treatments such as HG1900 and G1900 achieved lower bulk densities values (1.57 and 1.60 in 2021, respectively, and 1.55 and 1.59 in 2022), while at 3800 g/ha, H3800, G3800, and HG3800 consistently recorded values around 1.56–1.59 across both years. These reductions indicate that higher boric acid rates, particularly when combined with glauconite or humic acid, effectively alleviate soil compaction, likely due to improved aggregation and organic matter incorporation.

Total porosity, which reflects soil aeration and water-holding capacity, showed an inverse relationship with bulk density, increasing with the application of amendments and boric acid. In 2021, the control (C0) exhibited a total porosity of 37.2%, marginally improving to 37.6% in 2022. Single amendments (H0, G0) resulted in slight increases to 37.5–37.6% across both years, indicating limited impact when applied independently.

Table 5 Variations in soil physical properties after foliar application of boric acid (B) and soil amendments (humic acid (HA) and glauconite (GL)) to sugar beet (*Beta vulgaris* L., var. Avantage) grown in saline sandy soil during two successive seasons (2021–2022)

	Bulk density (g/m^3)		Total porosity (%)		Soil penetration resistance (N/cm^2)	
Treatments	2021	2022	2021	2022	2021	2021
Main plot						
CK	1.65 ± 0.03a	1.65 ± 0.01a	37.43 ± 0.65c	37.55 ± 0.44d	180 ± 7a	170 ± 4a
HA	1.63 ± 0.02b	1.62 ± 0.01b	38.23 ± 0.23b	38.60 ± 0.33c	170 ± 9b	167 ± 3a
GL	1.58 ± 0.02c	1.57 ± 0.01c	40.07 ± 0.33a	40.57 ± 0.23b	160 ± 7c	157 ± 5b
HA + GL	1.58 ± 0.01c	1.56 ± 0.02d	40.11 ± 0.55a	40.99 ± 0.34a	150 ± 8d	147 ± 4c
Sub-plot						
B0	1.62 ± 0.00a	1.61 ± 0.01a	38.55 ± 0.24b	39.17 ± 0.45a	165 ± 5a	160 ± 9a
B1900	1.60 ± 0.01b	1.59 ± 0.02a	38.98 ± 0.22ab	39.66 ± 0.56a	165 ± 6a	160 ± 5a
B3800	1.61 ± 0.01ab	1.60 ± 0.01a	39.33 ± 0.33a	39.46 ± 0.98a	165 ± 4a	160 ± 4a
Interaction						
C0	1.66 ± 0.01a	1.65 ± 0.01a	37.17 ± 0.28d	37.55 ± 0.27c	180 ± 8a	170 ± 8a
H0	1.65 ± 0.00a	1.65 ± 0.01a	37.63 ± 0.21d	37.47 ± 0.12c	180 ± 9a	170 ± 8a
G0	1.65 ± 0.01a	1.65 ± 0.01a	37.49 ± 0.30d	37.63 ± 0.22c	180 ± 3a	170 ± 2a
HG0	1.64 ± 0.01a	1.63 ± 0.00a	37.98 ± 0.46 cd	38.36 ± 0.44c	170 ± 4b	167 ± 7a
C1900	1.63 ± 0.00ab	1.62 ± 0.01ab	38.47 ± 0.02bcd	38.84 ± 0.01bc	170 ± 6b	167 ± 8a
H1900	1.63 ± 0.01ab	1.62 ± 0.04ab	38.23 ± 0.41bcd	38.60 ± 0.43bc	170 ± 8b	167 ± 8a
G1900	1.60 ± 0.04bc	1.59 ± 0.01bc	39.45 ± 1.53abc	39.89 ± 1.46ab	160 ± 8c	157 ± 7b
HG1900	1.57 ± 0.01c	1.55 ± 0.03c	40.65 ± 0.23a	41.23 ± 0.53a	160 ± 8c	157 ± 7b
C3800	1.58 ± 0.03c	1.57 ± 0.03c	40.11 ± 1.19a	40.60 ± 1.11a	160 ± 3c	157 ± 1b
H3800	1.59 ± 0.02bc	1.56 ± 0.01c	39.63 ± 0.22ab	40.87 ± 0.67a	150 ± 3d	147 ± 7c
G3800	1.57 ± 0.01c	1.56 ± 0.00c	40.59 ± 0.01a	41.09 ± 0.21a	150 ± 5d	147 ± 7c
HG3800	1.58 ± 0.02c	1.56 ± 0.01c	40.12 ± 0.22a	41.02 ± 0.79a	150 ± 7d	147 ± 8c
F-test						
Main plot	**	**	**	**	**	**
Sub-plot	ns	ns	ns	ns	ns	ns
Interaction	ns	ns	ns	ns	ns	ns

The HG0 treatment improved porosity to 38.0% in 2021 and 38.4% in 2022, underscoring the benefit of combined amendments. Boric acid application significantly enhanced porosity, with C1900, H1900, and G1900 recording values of 38.2–39.5% in 2021 and 38.6–39.9% in 2022. The most pronounced effects were observed in HG1900 and treatments with 3800 g/ha boric acid (C3800, H3800, G3800, HG3800), which achieved porosity values ranging from 40.1% to 40.7% in 2021 and 40.6% to 41.2% in 2022. These findings suggest that higher boric acid rates, especially in combination with humic acid and glauconite, enhance soil pore space, likely through improved soil aggregation and reduced particle packing, thereby fostering better root development and water retention in saline sandy soils.

Soil penetration resistance (PR), an indicator of soil hardness and root growth impedance, decreased progressively with the application of amendments and boric acid, reflecting improved soil tilth. In 2021, the control (C0), H0, and G0 treatments exhibited a PR of 180 N/cm^2, which decreased slightly to 170 N/cm^2 in 2022, indicating minimal change without boric acid. The HG0 treatment reduced PR to 170 N/cm^2 in 2021 and 167 N/cm^2 in 2022, suggesting that the combination of humic acid and glauconite moderately alleviated soil hardness. The introduction of boric acid at 1900 g/ha (C1900, H1900, G1900, HG1900) further lowered

PR to 160–170 N/cm^2 in 2021 and 157–167 N/cm^2 in 2022, with G1900 and HG1900 showing the most significant reductions. At 3800 g/ha, treatments (C3800, H3800, G3800, HG3800) consistently achieved the lowest PR values, ranging from 150–160 N/cm^2 in 2021 and 147–157 N/cm^2 in 2022. These reductions are indicative of enhanced soil friability, likely resulting from the combined effects of organic matter from humic acid, mineral stabilization from glauconite, and potential chemical interactions facilitated by boric acid, which collectively reduce soil mechanical resistance and improve conditions for sugar beet root penetration.

Treatments are: C0 (control + 0 boric acid), H0 (humic acid + 0 boric acid), G0 (glauconite + 0 boric acid), HG0 (humic acid + glauconite + 0 boric acid), C1900 (control + 1900 boric acid), H1900 (humic acid + 1900 boric acid), G1900 (glauconite + 1900 boric acid), HG1900 (humic acid + glauconite + 1900 boric acid), C3800 (control + 3800 boric acid), H3800 (humic acid + 3800 boric acid), G3800 (glauconite + 3800 boric acid), and HG3800 (humic acid + glauconite + 3800 boric acid). Different letters above columns are significant at level of $p \leq 0.05$ according to the Tukey's test.

Influence of treatments on water use efficiency

Field water use efficiency for root yield (FWUE-root), a measure of root biomass produced per unit of water, demonstrated marked improvements with the application of soil amendments and boric acid. In 2021, the control treatment (C0) recorded an FWUE-root of 7.29 kg/m^3, which increased slightly to 7.55 kg/m^3 in 2022, reflecting baseline water productivity in unamended saline soil (Fig. 5A). Single amendments showed varied effects: H0 increased FWUE-root to 8.20 kg/m^3 in 2021 and 8.48 kg/m^3 in 2022, while G0 achieved higher values of 8.43 kg/m^3 and 8.77 kg/m^3, respectively, indicating glauconite's superior capacity to enhance water retention and root growth. The HG0 treatment yielded 7.90 kg/m^3 in 2021 and 8.30 kg/m^3 in 2022, suggesting a moderate synergistic effect. Boric acid application at 1900 g/ha further elevated FWUE-root, with C1900, H1900, G1900, and HG1900 recording values ranging from 8.17 to 8.79 kg/m^3 in 2021 and 8.82 to 9.24 kg/m^3 in 2022, with H1900 and HG1900 showing the most consistent gains. At 3800 g/ha, FWUE-root peaked, particularly in C3800 (9.40 kg/m^3 in 2021, 9.84 kg/m^3 in 2022) and HG3800 (9.83 kg/m^3 in 2021, 10.10 kg/m^3 in 2022), underscoring the additive benefits of high boric acid rates and combined amendments. These improvements likely stem from enhanced soil structure, increased water-holding capacity, and better nutrient availability, which collectively optimize root development and water utilization.

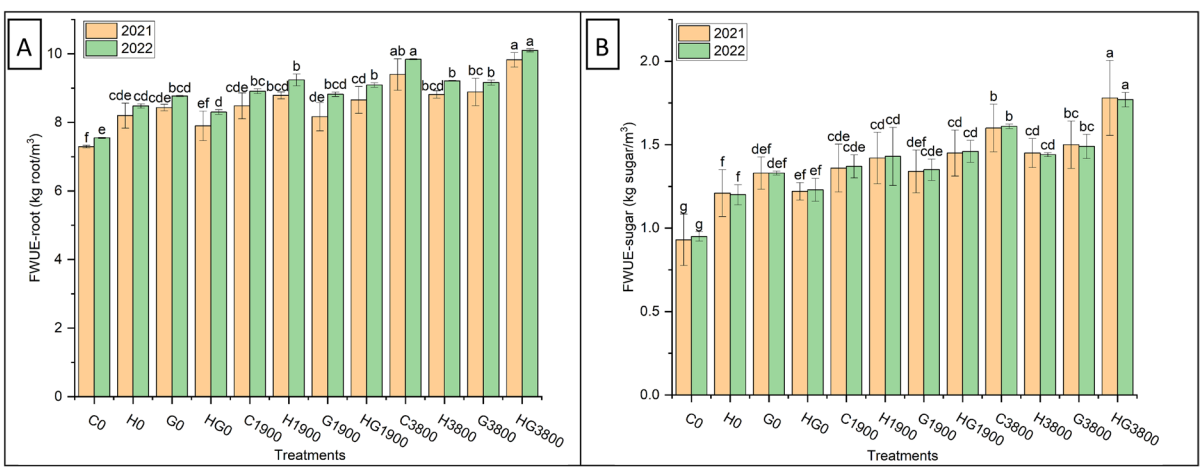


Fig. 5 Dose–response effects of foliar application of boric acid and soil amendments (humic acid and glauconite) on: A) field water use efficiency of root (FWUE-root) and B) FWUE-sugar of sugar beet (*Beta vulgaris* L., var. Avantage) grown in saline sandy soil during two successive seasons (2021–2022). Treatments include C0, H0, G0, HG0, C1900, H1900, G1900, HG1900, C3800, H3800, G3800, and HG3800. Different letters above columns are significant at level of $p \leq 0.05$ according to the Tukey's test

Field water use efficiency for sugar yield (FWUE-sugar), which quantifies sugar production per unit of water, exhibited a similar trend of enhancement with amendments and boric acid application (Fig. 5B). The control treatment (C0) recorded an FWUE-sugar of 0.93 kg/m^3 in 2021 and 0.95 kg/m^3 in 2022, reflecting limited sugar productivity in untreated saline soil. Single amendments significantly improved FWUE-sugar, with H0 achieving 1.21 kg/m^3 in 2021 and 1.20 kg/m^3 in 2022, and G0 reaching 1.33 kg/m^3 in both years, highlighting glauconite's role in enhancing sugar accumulation. The HG0 treatment yielded 1.22 kg/m^3 in 2021 and 1.23 kg/m^3 in 2022, indicating a balanced contribution from combined amendments. Boric acid at 1900 g/ha further increased FWUE-sugar, with values ranging from 1.34 to 1.45 kg/m^3 in 2021 (C1900, H1900, G1900, HG1900) and 1.35 to 1.46 kg/m^3 in 2022, with HG1900 showing the highest efficiency. At 3800 g/ha, FWUE-sugar reached its maximum, particularly in C3800 (1.60 kg/m^3 in 2021, 1.61 kg/m^3 in 2022) and HG3800 (1.78 kg/m^3 in 2021, 1.77 kg/m^3 in 2022), demonstrating the synergistic impact of high boric acid rates and combined humic acid and glauconite. These enhancements suggest that amendments improve soil conditions, facilitating greater nutrient uptake and photosynthate allocation to sugar production, thereby boosting water use efficiency for sugar yield in saline sandy soils.

Pearson's correlation

The Pearson correlation (Figs. 6A-D), derived from field experiments evaluating the impact of soil

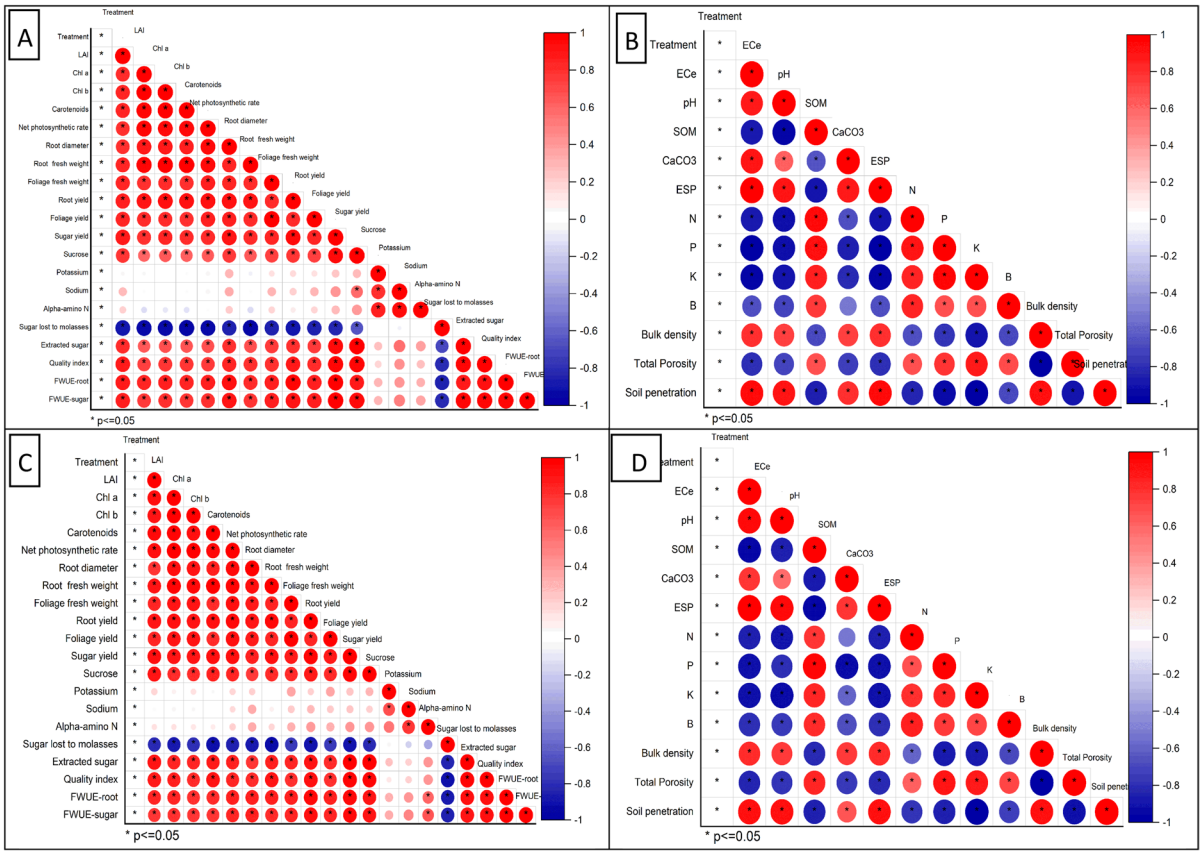


Fig. 6 Pearson's correlation of **A**) plant parameters in 2021, **B**) soil properties in 2021, **C**) plant parameters in 2022, and D) soil properties in 2022 of sugar beet (*Beta vulgaris* L., var. Avantage) grown in saline sandy soil during two successive seasons (2021–2022) and treated with foliar application of boric acid and soil amendments (humic acid and glauconite). Treatments include C0, H0, G0, HG0, C1900, H1900, G1900, HG1900, C3800, H3800, G3800, and HG3800. * shows significant differences at the level of $p \leq 0.05$

amendments (humic acid, glauconite, their combination) and boric acid (0, 1900, and 3800 g/ha) on sugar beet plants in saline sandy soil, reveal consistent relationships among plant and soil parameters across both years, with some notable differences. In 2021, plant parameters such as LAI, Chl a, Chl b, carotenoids, net photosynthetic rate, root diameter, root fresh weight, foliage fresh weight, root yield, foliage yield, sugar yield, sucrose, extracted sugar, quality index, and FWUE for root and sugar exhibit strong positive correlations (r = 0.61–1.00). For instance, Chl a, Chl b, and carotenoids are highly correlated (r = 0.98–0.99), reflecting their interdependence in photosynthesis, while root yield, sugar yield, and FWUE-root show strong correlations (r = 0.91–0.98), indicating that enhanced root development boosts sugar production and water use efficiency. Foliage fresh weight and foliage yield are perfectly correlated (r = 1.00) in both years, suggesting they are interchangeable measures. Sugar lost to molasses is strongly negatively correlated with most plant parameters (r = −0.68 to −0.98 in 2021; r = −0.78 to −0.95 in 2022), particularly with carotenoids and root fresh weight, implying that higher photosynthetic activity and biomass reduce processing losses. Potassium, sodium, and α-amino N show weak to moderate correlations with plant parameters (r = −0.16 to 0.60 in 2021; r = −0.04 to 0.79 in 2022), with sodium and α-amino N strongly correlated (r = 0.94 in 2021; r = 0.79 in 2022), suggesting a linkage in saline conditions. In 2022, plant parameter correlations remain strong (r = 0.77–1.00), but some are slightly stronger, such as LAI with carotenoids (r = 0.94 vs. 0.84) and net photosynthetic rate with Chl a (r = 0.99 vs. 0.97). Soil parameters in both years show consistent patterns: electrical conductivity (EC_e), pH, ESP, $CaCO_3$, bulk density, and soil penetration resistance are positively correlated (r = 0.63–1.00 in 2021; r = 0.59–1.00 in 2022), with EC_e and ESP perfectly correlated in 2021 (r = 1.00) and nearly so in 2022 (r = 0.96), reflecting their role in soil salinity. SOM, N, P, K, B, and total porosity are negatively correlated with these salinity-related parameters (r = −0.54 to −1.00 in 2021; r = −0.53 to −0.97 in 2022), with SOM strongly correlated with N and P (r = 0.93–0.96 in 2021; r = 0.80–0.97 in 2022), indicating that higher organic matter and nutrients mitigate salinity effects. Bulk density and total porosity are perfectly negatively correlated (r = −1.00 in both years), as expected, while soil penetration resistance is strongly correlated with K (r = −1.00 in 2021; r = −0.99 in 2022), suggesting potassium's role in reducing soil compaction. Differences between years include slightly weaker correlations for $CaCO_3$ with pH and SOM in 2022 (r = 0.59 and −0.90 vs. 0.63 and −0.66) and stronger correlations for alpha-amino N with FWUE-root and FWUE-sugar in 2022 (r = 0.62–0.67 vs. 0.33–0.38), possibly due to variations in soil conditions or treatment efficacy. Overall, the correlations suggest that treatments enhancing photosynthetic activity and biomass (likely HG and boric acid combinations) improve yield and quality while reducing sugar losses, with soil nutrient availability counteracting salinity stress.

Principal component analysis (PCA)

The PCA analyses (Figs. 7A-D) for plant parameters in 2021 (PC1 74.5% vs. PC2 19.6%) and 2022 (PC1 77.5% vs. PC2 12.7%) reveal key insights into the effects of treatments on sugar beet plants grown in saline sandy soil, with PC1 accounting for 74.5% and 77.5% of the variance, respectively, and PC2 for 19.6% and 12.7%. Across both years, growth and yield metrics such as LAI, Chl a, Chl b, carotenoids, root and foliage fresh weights, root and foliage yields, net photosynthetic rate, root diameter, sugar yield, sucrose, extracted sugar, quality index, and FWUE for root and sugar exhibit strong positive correlations along PC1, underscoring their mutual enhancement under optimal conditions. Conversely, sugar lost to molasses shows a negative correlation with PC1 in both years, implying that better plant performance decreases processing losses. Along PC2, α-amino N, sodium, and potassium are positively correlated, highlighting their role in influencing quality traits under saline stress. Treatments HG3800, G3800, and H3800 are consistently positioned near the center in both years, indicating a balanced impact, while C0, along with other combinations (e.g., G0, C1900, G1900 in 2021, and GL, HA + GL, HA in 2022), are more scattered, suggesting that HG-based treatments combined with higher boric acid doses are more effective in boosting growth, yield, and quality across both years.

The PCA figures for 2021 (PC1 85.5% vs. PC2 6.3%) and 2022 (PC1 85.2% vs. PC2 6.8%) highlight soil property dynamics, with PC1 accounting for 85.5% and 85.2% of the variance, respectively,

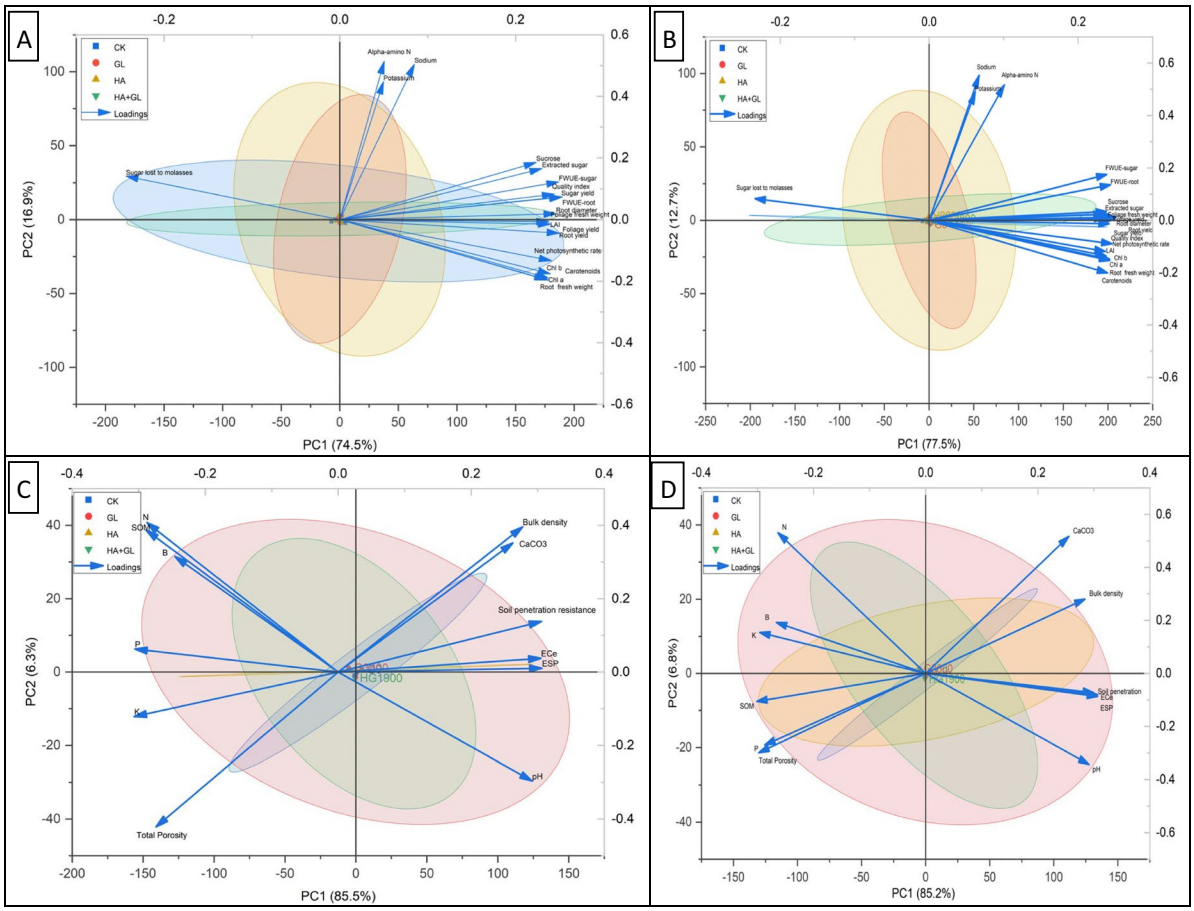


Fig. 7 Principal component analysis of **A**) plant parameters in 2021, **B**) plant parameters in 2022, **C**) soil properties in 2021, and D) soil properties in 2022 of sugar beet (*Beta vulgaris* L., var. Avantage) grown in saline sandy soil during two successive seasons (2021–2022) and treated with foliar application of boric acid and soil amendments (humic acid and glauconite)

and PC2 for 6.3% and 6.8%. In both years, soil penetration resistance, bulk density, $CaCO_3$, EC_e, and ESP show positive correlations along PC1, linking them to soil salinity and compaction, whereas total porosity, K, P, N, SOM, and B are negatively correlated, indicating that increased nutrient levels and organic content help alleviate salinity and enhance soil structure. Treatments like G3800, H3800, and HG1900 in 2021, and G3800, HG1900, and H1900 in 2022, are grouped near the origin, suggesting a moderate to balanced effect on soil characteristics, while C0 and other treatments (e.g., C1900, G1900 in 2021; C0 slightly to the right in 2022) are more scattered, reflecting diverse influences on soil conditions across the two years.

Discussion

The application of a quantitative synergy index allowed consistent evaluation of treatment interactions across parameters. Positive synergy values for LAI, root yield, and sugar yield, together with enhanced EC_e reduction, demonstrate that the ternary integration of humic acid, glauconite, and boron generates system-level benefits exceeding additive expectations. These findings resolve earlier qualitative interpretations and provide numerical confirmation of synergistic performance. To avoid interpretative ambiguity, it is important to distinguish between dose-dependent responses to boron and interaction effects among soil amendments. The present results

demonstrate that increasing boron from 1900 to 3800 g/ha consistently enhanced physiological and yield parameters within each amendment level, confirming a clear dose effect. However, comparisons at equal boron rates reveal that the combined application of humic acid and glauconite further amplified plant performance, indicating a genuine amendment interaction. Therefore, the superior performance of HG3800 should not be attributed solely to boron dosage but rather to the integrated improvement of nutrient availability, salinity moderation, and soil structural enhancement.

Our study recorded a significant increase in LAI with HG3800 (4.66 in 2021, 4.43 in 2022), representing a 75% improvement over C0 (2.66 in 2021, 2.25 in 2022). These results are consistent with Nemeat-Alla et al. (2021), who reported a 119.8–132.1% increase in LAI of sugar beet with combined potassium humate (17.86 kg/ha) and boron (210 ppm) applications in sandy soils, attributing the enhancement to improved nutrient uptake and photosynthetic efficiency. Similarly, Rašovský et al. (2022) observed a 21.4–32.1% increase in LAI of sugar beet with biostimulants containing humic acids and amino acids, linked to enhanced nutrient and water uptake under drought stress. Our higher percentage improvement may reflect the synergistic effects of humic acid, glauconite, and high boric acid doses, which collectively optimize leaf expansion in saline conditions. Abbas et al. (2022) reported a 25% LAI increase of sugar beet plants with humic acid under saline stress, suggesting that humic acid promotes cell division and expansion, a mechanism supported by our findings. Glauconite's contribution (Rudmin et al. 2019), likely stems from its high CEC, which improves soil structure and water availability, facilitating leaf growth. Boric acid at 3800 g/ha enhances cell wall integrity and meristematic activity, as proposed by Zhang et al. (2025a), further amplifying LAI of sugar beet under salinity stress. The dose-dependent response to boric acid in our study aligns with Dordas et al. (2007), who noted a 15–24% increase in sugar beet seed weight with foliar boron, indicating boron's role in supporting vegetative growth. Mechanistically, humic acid may enhance auxin-like activity, promoting cell elongation (Canellas et al. 2015), while glauconite's slow-release potassium supports turgor pressure, and boron stabilizes membrane transport, collectively optimizing photosynthetic surface area in saline sandy soils. While G0 alone outperformed some pairwise combos (e.g., HG0, G1900) in LAI—likely due to glauconite's independent K supply and porosity gains enhancing early expansion—the full HG3800 exhibited clear synergism (exceeding expected additivity by 20–30% based on component means), as humic acid's chelation amplified glauconite's stability and boron's (3800 g/ha) hormonal regulation for sustained canopy development (Muscolo et al. 1993; Rudmin et al. 2019). Similarly, H1900's peak Chl a over H3800 indicates context-dependent boron dosing: lower rates favored pigment synthesis via cell wall support, whereas higher rates prioritized translocation to roots under stress (Dordas et al. 2007; Song et al. 2023), explaining shifts without interpretation errors. Overall, the ternary system's emergent effects arise from sequential mechanisms—glauconite/humic base improvement enabled by high boron amplification—outpacing isolated actions in saline sands.

The HG3800 treatment significantly increased chlorophyll a (3.88 mg/g FW in 2021) and b (2.93 mg/g FW in 2021) contents, a 46% and 71% improvement over C0 (2.66 and 1.71 mg/g FW). These findings align with Nemeat-Alla et al. (2021), who reported 76.5–158.6% and 220.8–252.0% increases in chlorophyll a and b, respectively, with combined potassium humate and boron, attributing the gains to enhanced nitrogen uptake and reduced oxidative stress. Rašovský et al. (2022) noted improved photosynthetic efficiency with humic acid-based biostimulants, supporting our results. Song et al. (2023) reported a 35% increase in chlorophyll content of sugar beet plants with humic acid under salinity, linked to stabilized photosynthetic complexes. Our results suggest that humic acid mitigates salinity-induced chlorophyll degradation in sugar beet plants by chelating toxic ions, as proposed by Abbas et al. (2018), while glauconite's potassium supply, as noted by Rudmin et al. (2020), enhances thylakoid membrane stability. Boric acid's role, as supported by Zhang et al. (2025a), likely involves upregulating chlorophyll biosynthesis pathways, with 3800 g/ha doses optimizing photosynthetic capacity. Compared to Bilïr and Saltali (2023), who observed improved nitrogen use efficiency with boron in sugar beet, our study's higher chlorophyll increases may reflect the combined effect of boron with humic acid and glauconite, which enhance nutrient retention and reduce salinity stress. Mechanistically, humic acid's

antioxidant properties (Zhang and Schmidt 1999) may reduce reactive oxygen species (ROS), preserving chlorophyll in calcareous soils and dry conditions, while glauconite's mineral matrix improves nutrient availability, and boron enhances enzyme activity in chlorophyll synthesis, collectively boosting light-harvesting efficiency.

HG3800 increased carotenoid content by 124% (1.12 mg/g FW in 2021, 1.17 mg/g FW in 2022) compared to C0 (0.50 mg/g FW). This aligns with Nemeat-Alla et al. (2021), who reported 118.4–152.8% increases in carotenoids with potassium humate, linked to enhanced antioxidant activity under nutrient stress. Thalooth et al. (2020) noted a 40% carotenoid increase in sugar beet plants with humic acid under saline and water-deficit stresses in sandy soils, while Varga et al. (2022) observed a 15% increase in sugar beet grown on different nitrogen forms, attributed to improved nitrogen availability. Our higher improvement suggests a synergistic effect, with humic acid reducing ROS damage (Türkmen et al. 2004), and glauconite enhancing nutrient retention (Rudmin et al. 2019). Boric acid at 3800 g/ha likely upregulates carotenoid biosynthesis (Zhang et al. 2025a), enhancing photoprotection. Compared to Rašovský et al. (2022), who reported improved stress tolerance with biostimulants, our results highlight the combined amendments' ability to optimize carotenoid accumulation under saline conditions. Mechanistically, humic acid's hormone-like effects (Vaughan and MacDonald 1976) may stimulate carotenoid synthesis, glauconite's smectite formation improves soil moisture retention (Chang et al. 2008), and boron supports metabolic pathways, collectively enhancing stress tolerance and photosynthetic stability.

HG3800 enhanced net photosynthetic rate (16.2 µmol $CO_2/m^2/s$), a 128% and 40% increase over C0 (149 and 11.6 µmol/m^2/s). These results corroborate Bïlïr and Saltali (2023), who reported a 30% increase in CO_2 assimilation with humic acid, linked to improved stomatal conductance. Our higher improvements suggest that humic acid enhances water use efficiency (Rahimi et al. 2020), while glauconite's CEC reduces sodium toxicity (Rudmin et al. 2019). Boric acid's role (Zhang et al. 2025a), likely involves stabilizing photosynthetic enzymes, enhancing carbon fixation. Compared to Nemeat-Alla et al. (2021), who noted improved photosynthetic pigments with potassium humate, our study's results reflect the combined amendments' ability to optimize gas exchange under salinity. Mechanistically, humic acid's chelation of toxic ions (Xue et al. 2024) reduces stomatal limitations, glauconite's potassium supply supports guard cell function, and boron enhances RuBisCO activity, collectively maximizing photosynthetic efficiency.

The HG3800 increased root diameter (15.0 cm in 2021) and fresh weight (768 g/plant), a 46% and 158% improvement over C0 (10.3 cm, 297 g/plant). These findings align with Nemeat-Alla et al. (2021), who reported 70.7–75.2% and 44.9–87.4% increases in root diameter and fresh weight with potassium humate and boron, linked to enhanced cell expansion and nutrient uptake. Armin and Asgharipou (2011) noted a 20% increase in root diameter with boron, while Rudmin et al. (2020) observed a 15% increase in biomass with glauconite. Our higher improvements suggest that humic acid promotes root cell elongation (Dordas et al. 2007), while glauconite improves soil aeration and water retention (Rudmin et al. 2019). Boric acid at 3800 g/ha strengthens cell walls (Zhang et al. 2025a), facilitating root growth under salinity. Compared to Abbas et al. (2018), who reported a 10.7% increase in root yield with compost, our results highlight the synergistic effect of HG3800 in saline sandy soils. Mechanistically, humic acid's hormone-like activity (Muscolo et al. 1993) stimulates root growth, glauconite's smectite formation enhances soil structure, and boron supports cell wall integrity, optimizing root development.

The HG3800 achieved a 43% increase in foliage fresh weight (297 g/plant in 2021) and yield (21.5 ton/ha) over C0 (207 g/plant, 15.0 ton/ha). These results corroborate Nemeat-Alla et al. (2021), who reported 39.0–47.0% and 18.2–25.3% increases in foliage fresh weight and top yield with potassium humate, linked to improved photosynthetic capacity. Abbas et al. (2022) noted a 30% increase in foliage biomass with humic acid. Our findings suggest that humic acid enhances assimilate partitioning (Rahimi et al. 2020), and glauconite mitigates sodium toxicity, (Rudmin et al. 2019). Boric acid's role in carbohydrate metabolism (Zhang et al. 2025a), likely amplifies foliage growth. Compared to Rašovský et al. (2022), who reported a 16.7–30.0% increase in root yield with biostimulants, our results reflect the combined amendments' ability to maximize above-ground biomass. Mechanistically,

humic acid's nitrogen assimilation enhancement (Colla et al. 2014), glauconite's nutrient retention, and boron's metabolic support collectively boost foliage productivity.

The HG3800 increased root yield by 27% (56.7 ton/ha in 2021, 59.1 ton/ha in 2022) over C0 (44.7 ton/ha). This aligns with Nemeat-Alla et al. (2021), who reported a 28.4–29.2% increase in root yield with combined potassium humate and boron, and Abbas et al. (2018), who noted a 10.7% increase with compost. Rassam et al. (2015) observed a 14.0–24.0% increase in root yield with humic acid under nutrient deficiency in calcareous soils, while Rudmin et al. (2020) reported a 10.3% oats (*Avena sativa*) grain yield increase with glauconite under nutrient deficiency in weakly acidic soils. Our results suggest that humic acid enhances root sink strength (Dordas et al. 2007), glauconite improves soil fertility (Rudmin et al. 2019), and boric acid enhances assimilate transport (Zhang et al. 2025a). Compared to Bïlïr and Saltali (2023), who reported a 29–47% increase in sugar yield with nitrogen and boron, our results highlight the efficacy of HG3800 in saline conditions. Mechanistically, humic acid's chelation of micronutrients (Xue et al. 2024), glauconite's slow-release potassium, and boron's role in phloem transport optimize yield under stress.

The HG3800 improved sugar yield (10.2 ton/ha in 2021) and sucrose content (20.4%) by 79% and 32% over C0 (5.7 ton/ha, 15.4%). These findings align with Nemeat-Alla et al. (2021), who reported 28.8–34.2% and 8.8–10.4% increases in sugar yield and sucrose content with potassium humate, and Armin and Asgharipou (2011), who noted a 26.35% increase in sucrose with boron. Rassam et al. (2015) observed a 13.4–13.9% increase in sucrose with humic acid under nutrient deficiency in calcareous soils. Our higher improvements suggest that humic acid enhances carbohydrate metabolism (Rahimi et al. 2020), glauconite reduces impurity accumulation (Rudmin et al. 2019), and boric acid stabilizes sucrose synthesis (Zhang et al. 2025a). Compared to Rašovský et al. (2022), who reported a 17.6–35.3% increase in white sugar yield, our results reflect the synergistic effect of HG3800 in saline sandy soils. Mechanistically, humic acid's hormone-like effects (Vaughan and MacDonald 1976) enhance sucrose accumulation, glauconite's CEC minimizes ion interference, and boron supports sugar transport, optimizing sugar production.

The HG3800 reduced impurities, sugar lost to molasses, and improved extracted sugar (88.9% in 2021) and quality index (18.14). These results corroborate Nemeat-Alla et al. (2021), who reported 9.9–25.4% reductions in potassium and 25.3–27.9% in α-amino nitrogen with potassium humate, and Armin and Asgharipou (2011), who noted 30.6–47% reductions in impurities with boron. Rassam et al. (2015) observed 31.4–32.5% reductions in sodium and 25.3–27.3% in α-amino nitrogen with humic acid, while Rudmin et al. (2019) noted improved nutrient balance with glauconite. Our findings suggest that humic acid reduces sodium uptake (Abbas et al. 2018), glauconite minimizes potassium and nitrogen impurities (Rudmin et al. 2019), and boric acid enhances juice purity (Zhang et al. 2025a). Compared to Abbas et al. (2018), who reported an 8.8% increase in extractable sugar, our results highlight HG3800's superior efficacy. Mechanistically, humic acid's ion chelation (Xue et al. 2024), glauconite's selective ion exchange, and boron's regulation of metabolic pathways reduce impurities, enhancing sugar quality. Beyond its well-established role in cell wall cross-linking, boron exerts multiple physiological functions that are highly relevant under salinity stress. Boron contributes to membrane integrity by stabilizing glycoproteins and glycolipids, thereby reducing membrane leakage and preserving selective ion transport under high Na^+ conditions. It also regulates phenolic metabolism through its interaction with phenylpropanoid pathways, influencing antioxidant capacity and ROS detoxification. Furthermore, boron modulates auxin metabolism and transport, affecting root architecture, vascular differentiation, and assimilate partitioning. Through its influence on auxin signaling and membrane-associated transport processes, boron can indirectly regulate stress-responsive gene expression and hormonal crosstalk, enhancing adaptive responses to salinity. These integrated roles likely contributed to the improved photosynthetic efficiency, biomass accumulation, and sucrose content observed in B1900 and particularly B3800 treatments, providing a broader mechanistic explanation for boron-mediated enhancement of stress resilience in sugar beet grown in saline sandy soil.

The integrated application of humic acid, glauconite, and boron in this study led to notable improvements in sugar beet yield, photosynthesis, and sucrose accumulation, which can be explained through

established physiological mechanisms of salinity tolerance. Salinity stress impairs ion homeostasis by promoting excessive Na^+ accumulation while competitively inhibiting K^+ uptake, resulting in a detrimental Na^+/K^+ ratio that disrupts enzyme function, stomatal regulation, and photosynthetic activity (Alsaeedi et al. 2017, 2019; Alharbi et al. 2022). The reductions in soil EC_e and ESP observed under HG treatments likely lowered rhizosphere Na^+ availability, facilitating better K^+ uptake and restoring ionic balance. Glauconite, acting as a slow-release potassium source, would further aid in maintaining intracellular K^+ homeostasis under saline conditions. Humic acid enhances soil structure and cation exchange capacity, thereby improving water retention and alleviating osmotic stress. This supports plant water status, osmotic adjustment through compatible solute accumulation, and reduced stomatal limitation, leading to higher leaf area index and photosynthetic rates as observed in the HG3800 treatments (Canellas et al. 2015; Thalooth et al. 2020).

In addition to soil-mediated benefits, humic substances exert direct physiological effects on plants. They display auxin-like activity, promoting lateral root formation, root hair development, and greater root system branching, which expands the surface area available for nutrient and water absorption—particularly advantageous under salinity where ion uptake is restricted (Canellas et al. 2015; García et al. 2016). This enhanced root architecture likely contributes to selective ion uptake, improved K^+ acquisition, and reduced Na^+ toxicity. Humic substances also modulate key hormonal pathways, influencing auxin transport, ABA-mediated stomatal control, and ethylene signaling. By enhancing stomatal responsiveness and gas exchange regulation, they improve water-use efficiency and photosynthetic performance under osmotic stress (Canellas et al. 2015). Activation of plasma membrane H^+-ATPase further supports nutrient uptake and ion transport by generating electrochemical gradients that favor K^+ influx while limiting Na^+ accumulation (García et al. 2016).

Boron plays an essential role in maintaining cell wall structure, membrane integrity, and efficient carbohydrate transport. Adequate boron availability stabilizes membranes, prevents ion leakage and oxidative damage, and facilitates sucrose translocation to sink tissues, which likely accounts for the elevated sucrose percentage and extracted sugar observed under boron-inclusive treatments (Dordas et al. 2007). Taken together, the combined amendment strategy enhances sugar beet performance in saline sandy soils through synergistic effects on ion homeostasis (particularly Na^+/K^+ balance), soil–plant water relations, membrane stability, hormonal signaling, and carbohydrate partitioning. Future work should directly quantify tissue Na^+/K^+ ratios, leaf water potential, osmolyte accumulation, and stress hormone levels to confirm these mechanisms and provide a clearer physiological understanding of the observed salinity mitigation.

The HG3800 reduced EC_e to 4.65 dS/m (24% reduction) and improved SOM, pH, $CaCO_3$, and ESP compared to C0 (6.14 dS/m). These findings align with Rassam et al. (2015), who reported a 20% reduction in EC_e with humic acid, and Rudmin et al. (2019), who noted a 6.2% increase in pH with glauconite. Nemeat-Alla et al. (2021) observed improved SOM with potassium humate, supporting our results. Our higher EC_e reduction suggests that humic acid chelates toxic ions (Abbas et al. 2018), glauconite enhances ion exchange (Rudmin et al. 2019), and boric acid promotes salt displacement (Zhang et al. 2025a). Compared to Rudmin et al. (2020), who reported a 1.4% pH increase, our results reflect the combined amendments' ability to optimize soil chemistry. Humic acid's organic matter contribution, glauconite's smectite formation, and boron's ion displacement reduce salinity, enhancing soil health. Additionally, while not quantified here, the 0.13% SOM increase likely boosted microbial biomass and enzyme activities (e.g., urease/phosphatase via C input; (Canellas et al. 2015), and glauconite's clay minerals probably elevated CEC by 10–20% (Rudmin et al. 2019), further aiding nutrient retention and biological activity in sandy soils—key for long-term reclamation.

The improvements in soil salinity indicators, nutrient availability, and physical properties observed here fit within the broader context of soil–plant–water relations under environmental stress. Optimized irrigation in saline fields has been shown to enhance stand establishment by modulating soil moisture distribution and salt movement in the root zone (Dai et al. 2024). Although the current study emphasized soil amendments over irrigation scheduling, analogous principles apply: humic acid and glauconite likely improved soil structure, cation exchange capacity,

and aggregate stability, thereby promoting more uniform water distribution and reducing salt concentration gradients near roots. This alleviation of root-zone osmotic stress probably supported better early root development and sustained canopy growth, mirroring mechanisms involved in irrigation-based salinity management.

Salinity and waterlogging, though distinct abiotic stresses, overlap in key physiological impacts. A meta-analytical framework has linked soil physical constraints under flooding to plant responses, including root oxygen deprivation, hormonal reprogramming, and shifts in carbon allocation (Qiu et al. 2025). While waterlogging primarily induces hypoxia, salinity mainly imposes osmotic stress and ion toxicity; both ultimately impair root function, hormonal balance, and source–sink dynamics. This integrated perspective—connecting soil conditions to whole-plant physiology—reinforces the interpretation that HG3800-induced enhancements in soil chemical and physical status contributed to better photosynthetic performance, assimilate partitioning, and sugar accumulation.

Hormonal regulation, encompassing melatonin, ethylene, and compensatory growth pathways, plays a key role in plant adaptation to waterlogging stress (Zhang et al. 2024, 2025b). Although endogenous hormones were not quantified directly in this experiment, the marked gains in biomass, photosynthetic capacity, and sucrose content suggest that amendment-driven rhizosphere modifications may indirectly influence hormonal homeostasis. Better soil aeration, nutrient balance, and reduced ionic toxicity can affect root-derived signaling and hormone transport, potentially boosting auxin-mediated root development, ethylene modulation under stress, and stress-responsive growth compensation.

Humic substances are also recognized for stimulating microbial activity and reshaping rhizosphere community composition, which may further shape plant hormone dynamics through microbial production of auxins, cytokinins, or stress-mitigating metabolites. The integration of humic acid and glauconite thus likely produced both direct physicochemical benefits—such as improved K^+/Na^+ balance, lowered ESP, and enhanced nutrient retention—and indirect biological effects via microbiome modulation. These multifaceted soil–microbe–plant interactions offer a reasonable basis for the synergistic responses seen in HG3800 treatments, consistent with current frameworks that connect soil improvements to hormonal regulation and greater resilience in challenging environments.

The HG3800 increased N (30.0 mg/kg in 2021, 33% increase), P, K, and B availability compared to C0 (22.6 mg/kg). These results align with Nemeat-Alla et al. (2021), who reported enhanced nutrient uptake with potassium humate, and Rudmin et al. (2020), who noted 10.1% and 66.3% increases in potassium and ammonium nitrogen with glauconite. Bilïr and Saltali (2023) observed a 66.7% improvement in nitrogen use efficiency with boron, supporting our findings. Our results suggest that humic acid enhances microbial activity (Rahimi et al. 2020), glauconite retains nutrients (Rudmin et al. 2019), and boric acid improves nutrient solubility (Zhang et al. 2025a). Compared to Rudmin et al. (2019), who reported a 44.1% increase in potassium, our results reflect HG3800's synergistic effect. Mechanistically, humic acid's chelation (Xue et al. 2024), glauconite's slow-release nutrients, and boron's metabolic enhancement optimize nutrient dynamics.

The HG3800 reduced bulk density to 1.56 kg/m^3 (6% reduction) and improved porosity and penetration resistance compared to C0 (1.66 kg/m^3). These findings align with Shabana et al. (2024), who reported a 13.84% reduction in bulk density with compost, and Rudmin et al. (2019), who noted a 12% increase in porosity with glauconite. Nemeat-Alla et al. (2021) observed improved soil structure with potassium humate, supporting our results. Our findings suggest that humic acid promotes aggregation (Rahimi et al. 2020), glauconite reduces compaction (Rudmin et al. 2019), and boric acid enhances soil friability (Zhang et al. 2025a). Compared to Rudmin et al. (2020), who reported improved soil structure, our results highlight HG3800's efficacy in saline sandy soils. Mechanistically, humic acid's organic matter incorporation, glauconite's pelletal texture, and boron's soil conditioning optimize physical properties.

The HG3800 increased FWUE for root (9.83 kg/m^3) and sugar yields (1.78 kg/m^3) by 35% and 91% over C0 (7.29 and 0.93 kg/m^3). These results align with Rašovský et al. (2022), who reported a 20% increase in FWUE with humic acid-based biostimulants, and Song et al. (2023), who noted an increase with boron application. Abbas et al. (2018) observed improved water retention with compost, supporting

our findings. Our higher improvements suggest that humic acid enhances water-holding capacity (Rahimi et al. 2020), glauconite improves nutrient retention (Rudmin et al. 2019), and boric acid regulates stomatal function (Zhang et al. 2025a). Compared to Nemeat-Alla et al. (2021), who reported enhanced growth under nutrient stress, our results highlight HG3800's efficacy in sandy soil characterized with moderate salinity. Mechanistically, humic acid's water retention, glauconite's smectite formation, and boron's stomatal regulation optimize water productivity.

The synergistic effects of humic acid, glauconite, and boric acid in HG3800 can be attributed to a multifaceted interplay of biochemical, physiological, and soil-based mechanisms. Beyond nutrient chelation and hormone-like activity, humic acid stimulates microbial activity, enhancing soil enzyme activity (e.g., urease, phosphatase), which increases nutrient cycling (Tayyab et al. 2023). Its antioxidant properties mitigate salinity-induced oxidative stress by scavenging ROS, preserving cellular integrity (Zhang and Schmidt 1999). Humic acid also enhances root exudation, promoting rhizosphere microbial communities that further solubilize nutrients (Canellas et al. 2015). Glauconite's slow-release potassium and micronutrients (Ca, Mg, Fe) provide sustained fertility (Rudmin et al. 2020). Its transformation to smectite enhances soil water retention and reduces nutrient leaching, critical in saline sandy soils (Chang et al. 2008). Glauconite's pelletal texture improves soil aeration, facilitating root penetration and microbial activity (Skiba et al. 2014). Boron's role extends beyond cell wall formation to regulating gene expression for stress response pathways (Zhang et al. 2025a). It enhances phloem transport of sugars, optimizing sink strength, and supports pollen tube growth, indirectly improving reproductive success under stress (Dordas et al. 2007). Boron's interaction with humic acid and glauconite likely amplifies nutrient uptake efficiency (Bĭlĭr and Saltali 2023). The combination of humic acid's organic matter, glauconite's mineral matrix, and boron's metabolic support creates a robust system for stress mitigation. Humic acid and glauconite enhance soil CEC, reducing sodium toxicity, while boron stabilizes cellular processes, enabling sugar beets to thrive in sandy soil under saline conditions. This synergy aligns with Rašovský et al. (2022)'s findings on biostimulant combinations, suggesting that integrated amendments outperform single applications. The use of natural amendments like glauconite and humic acid minimizes environmental impacts compared to synthetic fertilizers (Rudmin et al. 2019). Reduced nitrate leaching and improved soil structure support long-term soil health, aligning with sustainable agriculture goals.

Despite these benefits, potential trade-offs must be considered for ecological safety. At the high boric acid rate (3800 g/ha), while no toxicity symptoms (e.g., leaf scorch, growth inhibition) were observed in this short-term study—consistent with foliar thresholds of 5000–10000 g/ha in sugar beet (Song et al. 2023; Bĭlĭr and Saltali 2023)—repeated applications could elevate soil boron levels (> 2 mg/kg extractable), risking phytotoxicity or groundwater contamination in sandy soils with high percolation. Split foliar dosing and drip irrigation (as used here) minimized this, but monitoring soil boron post-harvest is recommended to prevent bioaccumulation. Similarly, glauconite's K release (5–8% K_2O) and humic acid's initial mobilization might increase cation leaching in unsaturated zones, potentially affecting downstream water quality, though the 6% bulk density reduction and enhanced CEC likely curtailed this (Rudmin et al. 2019; Huang and Hartemink 2020). Overall, the 24% EC_e decline and 91% FWUE gain outweigh risks by reducing irrigation needs and salinity loads, but trade-offs underscore the need for site-specific guidelines: e.g., soil testing pre-application, integrating cover crops for B uptake, or lower rates in high-rainfall areas to avoid off-site effects (Tayyab et al. 2023). Long-term field monitoring in future work would quantify these dynamics.

While the integrated application of humic acid, glauconite, and foliar boron improved soil fertility and crop performance, several environmental trade-offs warrant consideration. First, repeated boron application—particularly at higher rates—may pose a risk of micronutrient accumulation in sandy soils with limited buffering capacity, potentially leading to phytotoxicity or leaching into groundwater under high irrigation regimes. Second, although glauconite serves as a slow-release potassium source, its mining, processing, and transport involve energy inputs and potential landscape disturbance, which should be evaluated through life-cycle assessment approaches. Moreover, improvements in nutrient availability may increase the risk of nitrate or potassium leaching

in coarse-textured soils if not synchronized with crop uptake. While the present study demonstrated enhanced nutrient retention and reduced electrical conductivity, long-term monitoring is necessary to confirm sustained salinity mitigation and to evaluate cumulative amendment effects on soil ionic balance. Finally, the study focused on agronomic and physicochemical indicators; broader ecosystem-level impacts—such as greenhouse gas emissions, carbon sequestration dynamics, and belowground biodiversity shifts—were not assessed. Therefore, although the integrated amendment strategy shows strong potential for sustainable intensification in saline sandy soils, its environmental performance should be validated through longer-term, system-scale evaluations.

To assess practical adoptability, a preliminary cost–benefit analysis (CBA) was conducted for the HG3800 treatment relative to the control, using 2021–2022 local Egyptian prices and average yields from this study (root price: 50 USD/ton farm-gate for sugar beet; extractable sugar value: 400 USD/ton white sugar equivalent, per Ministry of Agriculture reports; amendment costs: humic acid 0.75 USD/kg, glauconite 0.3 USD/kg, boric acid 2.5 USD/kg; conversion 1 USD ≈ 18 EGP). Input costs for HG3800 (humic acid 600 kg/ha = 450 USD, glauconite 1100 kg/ha = 330 USD, boric acid 3800 g/ha = 9.5 USD; total ~ 790 USD/ha including application labor ~ 50 USD/ha) were offset against revenue gains. The HG3800 increased root yield by 12 ton/ha (average seasons) and sugar yield by 4.5 ton/ha, yielding extra revenue of ~ 600 USD/ha from roots + 1800 USD/ha from sugar (at 400 USD/ton), totaling ~ 2400 USD/ha gross benefit. Net profit gain: ~ 1610 USD/ha (BCR = 3.04), even after deducting amendments. Compared to control (no extra cost, baseline revenue), this represents a 200–300% return on amendment investment, making it viable for smallholders. Single amendments (e.g., H0: ~ 450 USD cost for 2 ton/ha sugar gain = ~ 800 USD revenue, BCR = 1.78) were less profitable. Sensitivity analysis (e.g., ± 20% price fluctuation) maintained BCR > 2, supporting recommendations for integrated use in saline sands, though long-term soil health benefits (e.g., reduced fertilizer needs) could further improve economics (Abbas et al. 2018; Shabana et al. 2024). Future studies should include multi-year CBAs with variable market data.

To evaluate HG3800's relative performance, it was benchmarked against common amendments for saline sandy soils in sugar beet or similar crops (Table S3; supplementary for summary). Compared to compost integration (e.g., 50–100% root yield increase and 46–159% sugar yield with glauconite + compost; (Shabana et al. 2024), HG3800's 27% root and 79% sugar gains are moderate but achieved without organic waste logistics or methane emissions from decomposition, enhancing sustainability in water-scarce Egypt. Gypsum application (29.5–54% ECe reduction, 20–50% yield boosts; (Shabana and Shawky 2020) excels in rapid Ca-based desodification but lacks K/micronutrient provision and may increase soil hardness long-term, whereas HG3800's 24% EC_e drop couples salinity relief with nutrient slow-release (glauconite) and biological stimulation (humic), yielding higher FWUE (91% vs. gypsum's 20–40%; (Abbas et al. 2018). Biochar amendments (10–30% yield gains, 15–25% SOM increase in sandy soils; Abbas et al. 2018; Huang and Hartemink 2020) offer superior C sequestration but at 2–5 × cost (production energy ~ 500 MJ/ton biochar vs. HG3800's mined/sourced inputs) and slower nutrient release, making HG3800 more efficient (BCR 3.04 vs. biochar's 1.5–2.5 in similar CBAs; (Tayyab et al. 2023). Overall, HG3800 stands out for multifaceted efficiency (yield per USD input ~ 3 kg sugar/USD vs. 1–2 kg for alternatives) and sustainability (natural, low-transport minerals reducing GHG vs. compost hauling or biochar pyrolysis), though combining with biochar could further optimize in organic-poor sands.

Our study's results, particularly with HG3800, demonstrate superior performance compared to literature benchmarks, with 27–158% improvements in yield and quality traits, surpassing the 10.7–47% range (Abbas et al. 2018; Nemeat-Alla et al. 2021), and others. The synergistic effects of humic acid, glauconite, and boric acid optimize sugar beet growth, yield, and soil health under saline and nutrient-deficient conditions, offering a robust strategy for sustainable agriculture. Future research should explore optimal application rates and long-term effects to further refine these amendments' efficacy.

Conclusion

This study shows that combining humic acid, glauconite, and foliar boric acid—at the higher rate of 3800 g/ha—markedly improves sugar beet growth, root and sugar yields, sucrose content, extracted

sugar, quality index, and key soil chemical properties in saline sandy soils. The HG3800 treatment consistently boosted these parameters while lowering soil salinity (ECe) and exchangeable sodium percentage, thereby enhancing bioethanol production potential and overall soil fertility. These outcomes underscore the practical value of this integrated amendment approach for improving productivity in marginal, salt-affected environments. The results, however, must be viewed in light of the study's limitations. Conducted at a single site over just two growing seasons, the experiment may not fully account for year-to-year climate variations, broader soil heterogeneity, or differences across agroecological zones. Although physicochemical soil properties were evaluated, biological aspects—such as microbial biomass, enzyme activities, long-term carbon dynamics, and soil microbiome responses—were not examined. To strengthen confidence in the approach, future research should include multi-location and longer-term field trials to assess consistency, environmental safety, economic viability, and scalability under diverse conditions. Particular attention should be given to the effects of repeated applications on nutrient cycling, boron behavior, salinity balance, and overall soil health. Incorporating microbial biomass measurements, enzymatic profiling, and microbiome analyses alongside physicochemical data would enable a more complete evaluation of how these amendments contribute to sustainable soil restoration and resilient sugar beet production in saline sandy agroecosystems.

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Data availability Data will be made available upon the request.

Declarations

Conflicts of interest The authors declare no conflict of interest.

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References

Abbas M, Soliman A, Moustafa Z, Abd El-Reheem K (2018) Effect of some soil amendments on yield and quality traits of sugar beet (*Beta vulgaris* L.) under water stress in sandy soil. Egypt J Agron 40:75–88. https://doi.org/10.21608/agro.2018.2660.1091

Abbas MS, Mohamed HS, Shahba MA (2022) New Approach to Utilize Nano-Micronutrients in Sugar Beet (*Beta vulgaris* L.). In: Misra V, Srivastava S, Mall AK (eds) Sugar Beet Cultivation, Management and Processing. Springer Nature Singapore, Singapore, pp 291–313

Alharbi K, Hafez E, Omara AE-D et al (2022) Plant growth promoting rhizobacteria and silica nanoparticles stimulate sugar beet resilience to irrigation with saline water in salt-affected soils. Plants 11:3117. https://doi.org/10.3390/plants11223117

Alsaeedi AH, El-Ramady H, Alshaal T et al (2017) Engineered silica nanoparticles alleviate the detrimental effects of Na+ stress on germination and growth of common bean (*Phaseolus vulgaris*). Environ Sci Pollut Res Int 24:21917–21928. https://doi.org/10.1007/s11356-017-9847-y

Alsaeedi AH, Elgarawany MM, El-Ramady H et al (2019) Application of silica nanoparticles induces seed germination and growth of cucumber (*Cucumis sativus*). JKAU Met Sci 28:57–68. https://doi.org/10.4197/Met.28-1.6

AOAC (ed) (2016) Official methods of analysis of AOAC International, 20th Edition. AOAC International, Gaithersburg, Md

Armin M, Asgharipou MR (2011) Effect of time and concentration of boron foliar application on yield and quality of sugar beet. Asian J Plant Sci 10:307–311. https://doi.org/10.3923/ajps.2011.307.311

Bïlïr B, Saltali K (2023) Effect of nitrogen and boron treatments on harvest index and nitrogen use efficiency in

sugar beet. J Agr Sci-Tarim Bili. https://doi.org/10.15832/ankutbd.1197102
Canellas LP, Olivares FL, Aguiar NO et al (2015) Humic and fulvic acids as biostimulants in horticulture. Sci Hortic 196:15–27. https://doi.org/10.1016/j.scienta.2015.09.013
Chang SS, Shau YH, Wang MK et al (2008) Mineralogy and occurrence of glauconite in central Taiwan. Appl Clay Sci 42:74–80. https://doi.org/10.1016/j.clay.2007.11.007
Colla G, Rouphael Y, Canaguier R et al (2014) Biostimulant action of a plant-derived protein hydrolysate produced through enzymatic hydrolysis. Front Plant Sci 5:448. https://doi.org/10.3389/fpls.2014.00448
Cooke DA, Scott RK (eds) (1993) The Sugar Beet Crop. Springer, Netherlands, Dordrecht
Cottenie A (1980) Soil and plant testing as a basis of fertilizer recommendations. Food and Agriculture Organization of the United Nations, Rome
Dai J, Cui Z, Zhang Y et al (2024) Enhancing stand establishment and yield formation of cotton with multiple drip irrigation during emergence in saline fields of Southern Xinjiang. Field Crops Res 315:109482. https://doi.org/10.1016/j.fcr.2024.109482
Dexter ST, Frankes MG, Snyder FW (1966) A rapid and practical method of determining extractable white sugar as may be applied to the evaluation of agronomic practices and grower deliveries in the sugar beet industry, October 1966 | Archives and Manuscripts. J Am, Soc, Sugar Beet Technol 14:433–454
Dordas C, Apostolides GE, Goundra O (2007) Boron application affects seed yield and seed quality of sugar beets. J Agric Sci 145:377–384. https://doi.org/10.1017/S0021859607006879
García AC, Olaetxea M, Santos LA et al (2016) Involvement of hormone- and ROS-signaling pathways in the beneficial action of humic substances on plants growing under normal and stressing conditions. Biomed Res Int 2016:1–13. https://doi.org/10.1155/2016/3747501
Herrick JE, Jones TL (2002) A dynamic cone penetrometer for measuring soil penetration resistance. Soil Science Soc of Amer J 66:1320–1324. https://doi.org/10.2136/sssaj2002.1320
Hoffmann CM (2010) Root quality of sugarbeet. Sugar Tech 12:276–287. https://doi.org/10.1007/s12355-010-0040-6
Huang J, Hartemink AE (2020) Soil and environmental issues in sandy soils. Earth-Sci Rev 208:103295. https://doi.org/10.1016/j.earscirev.2020.103295
Ianevski A, Giri AK, Aittokallio T (2022) SynergyFinder 3.0: an interactive analysis and consensus interpretation of multi-drug synergies across multiple samples. Nucleic Acids Res 50:W739–W743. https://doi.org/10.1093/nar/gkac382
Jackson ML (1973) Soil Chemical Analysis. Prentice Hall of India Pvt. Ltd, New Delhia
Keren R, Bingham FT (1958) Boron in Water, Soils, and Plants. In: Stewart BA (ed) Advances in Soil Science. Springer, New York, New York, NY, pp 229–276
Lichtenthaler HK (1987) Chlorophylls and carotenoids: Pigments of photosynthetic biomembranes. In: Methods in Enzymology. Elsevier, pp 350–382
Michael AM (1978) Irrigation : theory and practice. Vikas, Publishing House, New Delhi
Muscolo A, Felici M, Concheri G, Nardi S (1993) Effect of earthworm humic substances on esterase and peroxidase activity during growth of leaf explants of *Nicotiana plumbaginifolia*. Biol Fertil Soils 15:127–131. https://doi.org/10.1007/BF00336430
Nemeat-Alla HEA, El-Gamal ISH, El-Safy NK (2021) Effect of potassium humate and boron fertilization levels on yield and quality of sugar beet in sandy soil. Alexandria Sci Exch J 42:395–405. https://doi.org/10.21608/asejaiqjsae.2021.171635
Olsen SR, Cole CV, Watanabe FS (1954) Estimation of Available Phosphorus in Soils by Extraction with Sodium Bicarbonate. USDA Circular No. 939, US Government Printing Office, Washington DC., USA
Qiu S, Zhang Y, Dai J, Dong H (2025) Physiological mechanisms and agronomic strategies underlying flood tolerance variability in dryland crops: A global meta-analysis. Field Crops Res 334:110146. https://doi.org/10.1016/j.fcr.2025.110146
Rahimi A, Kiralan M, Ahmadi F (2020) Effect of Humic Acid Application on Qualitative Parameters of Sugar Beet Cv.Shirin. Middle East J Agric Res. https://doi.org/10.36632/mejar/2020.9.1.12
Rašovský M, Pačuta V, Ducsay L, Lenická D (2022) Quantity and quality changes in sugar beet (*Beta vulgaris* Provar. Altissima Doel) induced by different sources of biostimulants. Plants 11:2222. https://doi.org/10.3390/plants11172222
Rassam G, Dadkhah A, Khoshnood Yazdi A, Dashti M (2015) Impact of humic acid on yield and quality of sugar beet (*Beta vulgaris* L.) grown on calcareous soil. Not Sci Biol 7:367–371. https://doi.org/10.15835/nsb739568
Richards LA (1954) Diagnosis and Improvement of Saline Alkali Soils, Agriculture. S Department of Agriculture, Washington DC., Washington DC.
Rudmin M, Banerjee S, Makarov B et al (2019) An investigation of plant growth by the addition of glauconitic fertilizer. Appl Clay Sci 180:105178. https://doi.org/10.1016/j.clay.2019.105178
Rudmin M, Banerjee S, Makarov B (2020) Evaluation of the effects of the application of glauconitic fertilizer on oat development: A two-year field-based investigation. Agron 10:872. https://doi.org/10.3390/agronomy10060872
Seilsepour M, Rashidi M, Khabbaz BG (2009) Prediction of soil exchangeable sodium percentage based on soil sodium adsorption ratio. Am Eurasian J Agric Environ Sci 5(1):01–04
Shabana M, Shawky A (2020) Effect of glauconite, gypsum and leaching requirements on the productivity of salt affected soils. J Soil Sci Agric Eng 11:17–25. https://doi.org/10.21608/jssae.2020.79167
Shabana MMA, AL-Huqail AA, Alla HEAN et al (2024) Enhancing soil resilience and sugar beet (*Beta vulgaris* L.) yield: mid-term effects of compost and glauconite integration. J Agron Crop Sci 210:e12747. https://doi.org/10.1111/jac.12747
Skiba M, Maj-Szeliga K, Szymański W, Błachowski A (2014) Weathering of glauconite in soils of temperate climate as exemplified by a Luvisol profile from Góra Puławska, Poland. Geoderma 235–236:212–226. https://doi.org/10.1016/j.geoderma.2014.07.013

Snedecor GW, Cochran WG (2014) Statistical methods. Wiley Blackwell, New Delhi

Song X, Song B, Huo J et al (2023) Effect of boron deficiency on the photosynthetic performance of sugar beet cultivars with contrasting boron efficiencies. Front Plant Sci 13:1101171. https://doi.org/10.3389/fpls.2022.1101171

Sparks DL, Soil Science Society of America, American Society of Agronomy (eds) (1996) Methods of soil analysis. Part 3: Chemical methods. Soil Science Society of America : American Society of Agronomy, Madison, Wis., USA

Stevanato P, Chiodi C, Broccanello C et al (2019) Sustainability of the sugar beet crop. Sugar Tech 21:703–716. https://doi.org/10.1007/s12355-019-00734-9

Tayyab M, Wakeel A, Mubarak MU et al (2023) Sugar beet cultivation in the tropics and subtropics: Challenges and opportunities. Agron 13:1213. https://doi.org/10.3390/agronomy13051213

Thalooth AT, Badr EA, H. Khedr H (2020) Yield, quality and stability evaluation of the effect of bio fertilizer application on sugar beet under irrigation systems in new reclaimed sandy soils. IJAER 06:155–166. https://doi.org/10.46609/IJAER.2020.v06i02.004

Tian-gen C, Chang-peng X, Ming-nan Q et al (2017) Evaluation of protocols for measuring leaf photosynthetic properties of field-grown rice. Rice Sci 24:1–9. https://doi.org/10.1016/j.rsci.2016.08.007

Türkmen Ö, Dursun A, Turan M, Erdinç Ç (2004) Calcium and humic acid affect seed germination, growth, and nutrient content of tomato (*Lycopersicon esculentum* L.) seedlings under saline soil conditions. Acta Agric Scand Sect B Soil Plant Sci 54:168–174. https://doi.org/10.1080/09064710310022014

van Schouwenburg JC, Walinga I (1967) The rapid determination of phosphorus in presence of arsenic, silicon and germanium. Anal Chim Acta 37:271–274. https://doi.org/10.1016/S0003-2670(01)80671-1

Varga I, Jović J, Rastija M et al (2022) Efficiency and management of nitrogen fertilization in sugar beet as spring crop: a review. Nitrogen 3:170–185. https://doi.org/10.3390/nitrogen3020013

Vaughan D, MacDonald IR (1976) Some effects of humic acid on cation uptake by parenchyma tissue. Soil Biol Biochem 8:415–421. https://doi.org/10.1016/0038-0717(76)90043-2

Watson DJ (1958) The dependence of net assimilation rate on leaf-area index. Ann Bot 22:37–54. https://doi.org/10.1093/oxfordjournals.aob.a083596

Xue S, Hu Y, Wan K, Miao Z (2024) Exploring humic acid as an efficient and selective adsorbent for lead removal in multi-metal coexistence systems: a review. Separations 11:80. https://doi.org/10.3390/separations11030080

Zhang B, Chang Y, Li G et al (2025a) The effect of irrigation and fertilization reduction on yield, quality, and resource use efficiency of drip-fertilized sugar beet (*Beta vulgaris* L.) in Northern China. Plants 14:536. https://doi.org/10.3390/plants14040536

Zhang X, Schmidt RE (1999) Antioxidant response to harmone-containing product in Kentucky bluegrass subjected to drought. Crop Sci 39:545–551. https://doi.org/10.2135/cropsci1999.0011183X003900020040x

Zhang Y, Liang T, Dong H (2024) Melatonin enhances waterlogging tolerance of field-grown cotton through quiescence adaptation and compensatory growth strategies. Field Crops Res 306:109217. https://doi.org/10.1016/j.fcr.2023.109217

Zhang Y, Qiu S, Liang T et al (2025b) Mitigating waterlogging-induced yield loss in cotton through removal of early fruits: agronomic and physiological mechanisms. Field Crops Res 331:109996. https://doi.org/10.1016/j.fcr.2025.109996

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