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Potassium fertilization and biochar amendment synergistically improve barley growth and nutrient uptake under drought and salinity stress

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ABSTRACT

Drought and salinity are the primary constraints for barley production in arid and semi-arid regions. Although potassium (K) fertilization and biochar amendment each individually mitigate these stresses, their interactive effects under combined drought and salinity conditions remain poorly characterized for barley. A four-factor greenhouse pot experiment was conducted using a completely randomized factorial design comprising three drought levels (D0: 100%, D1: 75%, D2: 50% field capacity), three K rates (K0: 0, K1: 160, K2: 320 kg K_2SO_4 ha^{-1}), two biochar rates (B0: 0, B1: 18 t ha^{-1} of olive mill waste biochar), and two soil types (non-saline, NS: EC = 0.37 dS m^{-1}; saline, S: EC = 6.23 dS m^{-1}), yielding 36 treatment combinations replicated four times (144 pots). Response variables included shoot length, shoot and root fresh and dry weights, chlorophyll index (SPAD), and leaf macronutrient concentrations (N, P, K, Ca, Mg) and soil organic matter. Severe drought (D2) reduced shoot fresh weight by 44% and root fresh weight by 36% in non-saline soil without amendments. The K1 × B1 combination recovered 83% of the well-watered, unamended shoot fresh weight under D2 in non-saline soil and performed consistently as the superior treatment under saline conditions. The K2 rate provided no consistent advantage over K1 and reduced root dry weight in several combinations, suggesting ionic imbalance at supraoptimal supply. SPAD values were not significantly affected by drought, indicating chlorophyll stability in this cultivar under the tested stress range. All four-way interactions (D × K × B × S) were statistically significant for most morphological and nutritional variables ($p < 0.01$). Co-application of biochar (18 t ha^{-1}) with K fertilization at 160 kg ha^{-1} is an effective strategy to maintain vegetative growth performance in water-limited, saline-prone environments. Field-scale validation including grain yield and water-use efficiency measurements is necessary before definitive agronomic recommendations can be made.

Keywords biochar, *Hordeum vulgare*, potassium fertilization, drought tolerance, soil salinity, macronutrient uptake.

INTRODUCTION

Barley (*Hordeum vulgare* L.) is ranked fourth globally in cereal production and is a cornerstone crop in arid and semi-arid regions, valued for its relative tolerance of marginal environments (Al Azzawi et al., 2021; Rusan, 2023). Despite this resilience, yields in the Middle East and North Africa are severely constrained by drought, which frequently co-occurs with soil salinity – two stresses that together represent the most significant abiotic barriers to food security in these regions (Hu and Schmidhalter 2005; Zhang et al., 2020).

Drought reduces barley growth through multiple mechanisms: declining turgor pressure restricts cell elongation and division, reduced soil water potential limits the mass flow and diffusion of nutrients to root surfaces, and stomatal closure constrains CO_2 assimilation and photosynthesis (Anjum et al., 2011; Qiao et al., 2024). Salinity compounds these effects by imposing additional osmotic stress and introducing toxic Na^+ and Cl^- ions that compete with beneficial cations at uptake sites (Hu and Schmidhalter, 2005). Barley yield losses under combined drought–salinity stress are therefore greater than under either stressor alone, necessitating management strategies that address both soil water and ionic dynamics simultaneously.

Potassium (K) is indispensable for drought tolerance. As the dominant osmoticum in guard cells, K regulates stomatal aperture and transpiration efficiency; it activates more than 60 enzymes involved in photosynthesis and respiration; and it enables long-distance phloem transport of assimilates (Hawkesford et al., 2012; Hasanuzzaman et al., 2018). Under drought, reduced soil moisture limits K^+ diffusion to root surfaces, creating a feedback whereby K deficiency exacerbates stress sensitivity (Yang et al., 2022; Cakmak and Rengel, 2024). Exogenous K application has been shown to restore turgor, sustain chlorophyll content, and maintain biomass production under water-deficit conditions in various cereals (Hassan et al., 2017; Sardans and Peñuelas, 2021). However, supraoptimal K rates can induce ionic imbalances—particularly antagonism with Ca^{2+} and Mg^{2+}—that may negate benefits (Sardans and Peñuelas, 2021).

Biochar—the stable, carbon-rich solid produced by thermal decomposition of organic biomass under limited oxygen—offers complementary soil-mediated benefits. Its porous micro-architecture increases soil water retention, aeration, and cation exchange capacity (CEC), thereby increasing water availability and nutrient residence time in the root zone (Razzaghi et al., 2020; Alkharabsheh et al., 2021). Olive mill waste biochar is particularly relevant to Mediterranean and Middle Eastern agroecosystems, where this by-product is abundantly available, and prior work has demonstrated its potential to improve barley and wheat growth under rainfed conditions (Albalasmeh et al., 2023; Albalasmeh et al., 2024). Yet no published work has examined olive mill waste biochar specifically in combination with K fertilization under drought and salinity co-stress in barley, representing a second dimension of novelty in the present study.

Despite a growing literature documenting the independent benefits of K fertilization and biochar amendment, the existing combined-application studies share three systematic limitations that constrain their applicability to barley production systems in the Middle East. First, studies combining K and biochar in cereals have focused predominantly on wheat (Chowdhury et al., 2024; Saudy et al., 2023) and maize (Rahman et al., 2025), with barley receiving almost no attention despite its greater importance as a subsistence crop in water-limited environments. Second, drought and salinity have invariably been tested as separate stressors rather than as co-occurring variables in the same factorial frame, even though both stresses are simultaneously present in most irrigated lowland soils of the Jordan Valley and similar semi-arid regions. Third, the biochar feedstock used in the vast majority of published studies – rice straw, wood chips, and poultry manure – differs fundamentally from olive mill waste, which is generated at scale across the Mediterranean and Middle East without a sustainable disposal pathway, making its agronomic valorization both scientifically relevant and practically urgent. Chowdhury et al. (2024) reported that co-application of biochar and foliar K_2SO_4 in wheat increased grain yield by 43% relative to drought-stressed, unamended controls. Rahman et al. (2025) demonstrated comparable synergies in maize, with the combined treatment reducing electrolytic leakage by 35–43% under different drought levels. A systematic search of Web of Science and Scopus using the terms "biochar AND potassium AND barley AND drought" and "biochar AND potassium AND salinity AND barley" returned no study that simultaneously evaluated all four variables, drought intensity, K rate, biochar amendment, and soil salinity, in a single factorial design for barley. This represents a fundamental knowledge gap, because the response of a crop to any single management input cannot reliably predict its response to the combined application of multiple inputs under multiple co-occurring stresses; interaction effects are not predictable from main effects alone and must be measured directly.

The present study was designed to address these gaps using a four-factor greenhouse pot experiment. Three hypotheses were tested: (i) that co-application of olive mill waste biochar and K fertilization would produce a synergistic improvement

in barley vegetative growth and macronutrient uptake greater than the sum of their individual effects, with the magnitude of synergy increasing under more severe drought; (ii) that an optimal K rate would exist beyond which ionic antagonism with Ca^{2+} and Mg^{2+} would reduce rather than further improve growth under severe combined stress; and (iii) that soil salinity would significantly modify the magnitude and direction of the biochar × K interaction, such that treatment recommendations cannot be generalized across saline and non-saline conditions without soil-type-specific calibration. By testing these hypotheses within a fully factorial design that simultaneously crosses drought level, K rate, biochar rate, and soil salinity, this study provides a level of interaction analysis not previously available for barley and directly informs integrated soil management recommendations for water-limited, salt-affected agroecosystems in the Middle East. It is explicitly acknowledged that this experiment measured vegetative-stage responses only; grain yield, yield components, and water-use efficiency were not assessed, and extrapolation to field productivity should be made cautiously pending field-scale validation.

MATERIAL AND METHODS

Soil collection and characterization

Surface soil (0–30 cm) was collected from an agricultural field in the Jordan Valley, Jordan, representing two salinity classes: a non-saline soil (NS; EC = 0.37 dS m^{-1}) and a saline soil (S; EC = 6.23 dS m^{-1}). Samples were air-dried, crushed with a rubber mallet, and passed through a 2-mm sieve. Physical and chemical properties were determined using standard methods (Table 1): particle-size distribution by the hydrometer method; pH in a 1:1 soil-to-water suspension; EC in saturation extract; organic matter by the Walkley–Black wet oxidation method; bulk density by the undisturbed core method; and exchangeable K by extraction with 1 M ammonium acetate (pH 7) followed by flame photometry.

Biochar production and characterization

Biochar was produced from solid olive mill waste (Jift) by slow pyrolysis at 350 °C in a muffle furnace for 1 h under limited oxygen, following the protocol of Albalasmeh et al. (2024). The top layer (condensed volatiles) was discarded; the remainder was homogenized, ground to < 1 mm, and stored in sealed containers until use. Characterization (Table 2) included: pH by ASTM D3838-05 (2017); EC by Rhoades (1982); ash content by ASTM D3176; C, H, N, S by elemental analysis; K and P by ICP-OES after aqua regia digestion; and specific surface area by the Brunauer–Emmett–Teller (BET) N_2 adsorption method. The field application rate of 18 t ha^{-1} was converted to a pot-equivalent rate, assuming incorporation into the upper 0–15 cm layer at a bulk density of 1.3 g cm^{-3}, yielding 83 g of biochar per 6-kg pot (1.38% w/w), which was thoroughly mixed with the soil before planting. A single biochar rate of 18 t ha^{-1} (≈1.4% w/w in the 0–20 cm layer) was selected because recent meta-analyses and field trials identify this range as the agronomic optimum for biochars in saline and semi-arid soils: a synthesis of 113 saline-alkali studies reported 10–20 t ha^{-1} as the most effective rate for raising yield while reducing Na^+ and salinity (Zhang et al., 2025), and a three-year field trial reported an optimum of 15–20 t ha^{-1} under sufficient irrigation (Guan et al., 2024). Higher rates (>50 t ha^{-1})

Table 1. Physical and chemical properties of the two experimental soils

Parameter	Non-saline soil (NS)	Saline soil (S)	Method
pH	7.09	7.79	1:1 soil:water
EC (dS m^{-1})	0.37	6.23	Saturation extract
Sand (%)	22	38	Hydrometer
Silt (%)	46	37	Hydrometer
Clay (%)	32	25	Hydrometer
Texture class	Silt loam	Loam	USDA
Bulk density (g cm^{-3})	1.33	1.41	Core method
Organic matter (%)	1.37	1.23	Walkley–Black
Available K (mg kg^{-1})	273	126	NH_4-acetate

Table 2. Physicochemical properties of the olive mill waste-based biochar used in the experiment

Parameter	Value
Feedstock	Olive mill solid waste (Jift)
Pyrolysis temperature (°C)	350
pH	8.62
EC (dS m^{-1})	1.27
Specific surface area (m^2 g^{-1})	117.35
Ash content (%)	27.01
C (%)	81.68
N (%)	3.78
H (%)	5.12
S (%)	0.47
O (%)	8.95
K (g kg^{-1})	35.4
P (g kg^{-1})	7.2
C:N ratio	21.6
Field application rate (t ha^{-1})	18 (≡ 83 g per 6-kg pot; 1.38% w/w)

and very high w/w doses have been shown to depress crop growth and microbial function (Su et al., 2024; Wu et al., 2024; Zhu et al., 2023). A single, well-justified rate was therefore adopted to preserve replication and statistical power for the potassium × biochar × stress interaction that is the focus of this study.

Experimental design and treatments

The experiment was conducted in a greenhouse at the Jordan University of Science and Technology during the 2024 growing season. A four-factor completely randomized design (CRD) was employed, comprising drought level (D), potassium rate (K), biochar amendment (B), and soil type (S). This arrangement yielded 3 × 3 × 2 × 2 = 36 treatment combinations, each replicated four times, for 144 experimental units (plastic pots; top diameter 22 cm, bottom diameter 18 cm, height 24 cm; 6 kg air-dried soil per pot).

Barley (*Hordeum vulgare* L. cv. Rum) seeds were surface-sterilized (1% NaOCl, 5 min), rinsed, and sown at five seeds per pot; pots were thinned to three uniform seedlings at emergence. Basal fertilization was applied uniformly to all pots at rates equivalent to diammonium phosphate (130 kg ha^{-1}) and urea (122 kg ha^{-1}), applied 14 days after sowing. Potassium sulfate (K_2SO_4) was applied in two equal split doses (14 and 42 days after sowing) at rates of 0 (K0), 160 (K1), or 320 (K2) kg ha^{-1}.

Pot field capacity (FC) was determined gravimetrically: pots were saturated from the base, covered to suppress evaporation, drained freely for 24 h, and weighed. Drought treatments were imposed by maintaining soil moisture at 100% (D0), 75% (D1), or 50% (D2) of FC throughout the experiment. Pots were weighed three times per week and irrigated with distilled water to restore the target moisture level. All pots were repositioned randomly within the greenhouse weekly to minimize positional effects.

Morphological measurements

Plants were harvested at the late vegetative/early reproductive stage (approximately 90 days after sowing). Shoot length (SL; cm) was measured from the soil surface to the tip of the longest tiller. Plants were separated into shoot and root fractions; shoot fresh weight (SFW) and root fresh weight (RFW) were recorded immediately on a digital balance (±0.01 g). Samples were oven-dried at 65 °C to constant mass for shoot dry weight (SDW) and root dry weight (RDW). Dried material was ground (Wiley mill, 1-mm screen) and stored for analysis.

Chlorophyll content index

Leaf chlorophyll content was estimated non-destructively using a SPAD-502 chlorophyll meter (Konica Minolta, Japan) on the flag leaf of each tiller. Three readings per leaf were taken at the basal, mid, and apical thirds of the leaf blade; the mean was recorded. An average SPAD value per pot was calculated across all sampled leaves. SPAD values are strongly correlated with extractable chlorophyll concentrations in barley (Uddling et al., 2007), permitting non-destructive, repeated assessment without compromising biomass data.

Macronutrient analysis

Leaf total nitrogen (N) was determined by the micro-Kjeldahl method (Bremner and Jenkinson, 1960). Phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg) were determined by dry-ashing (0.5 g at 550 °C for 6 h) followed by dissolution in 10% HCl. P was determined colorimetrically using the ascorbic acid–molybdate blue method at 882 nm; K by flame photometry; and

Ca and Mg by atomic absorption spectrometry (Cottenie, 1982). Soil organic matter (OM) was determined at harvest by loss-on-ignition at 550 °C (4 h) on a composite sub-sample from each pot.

Statistical analysis

Data were analyzed in R version 4.3.1 (R Core Team, 2023). A four-factor ANOVA was performed using a full factorial model including all main effects and all pairwise, three-way, and four-way interaction terms (D × K × B × S), with replication as a blocking factor. Prior to ANOVA, normality was assessed by the Shapiro–Wilk test and homogeneity of variance by Levene's test; data were log-transformed where assumptions were violated and back-transformed for presentation. Mean separation used Tukey's honestly significant difference (HSD) test at $p \leq 0.05$. The ANOVA significance summary across all response variables is presented in Table 3, and selected treatment means are given in Table 4.

RESULTS

Effects of drought, potassium, biochar and soil type on shoot and root morphology

Drought stress, K rate, biochar amendment, and soil type all exerted significant ($p < 0.001$) main effects on SL, SFW, SDW, RFW, and RDW; all two-way and three-way interactions, and the four-way D × K × B × S interaction, were significant for most variables (Table 3). In non-saline soil without amendments (D0K0B0), progressive drought reduced SFW from 321 g (D0) to 249 g (D1, −22%) and 180 g (D2, −44%), and RFW from 128 g to 103 g (−19%) and 81.7 g (−36%). In saline soil (D0K0B0), corresponding values were lower throughout; SFW declined from 273 g (D0) to 152 g (D2, −44%) and RFW from 109 g to 68.9 g (−37%), reflecting the additional osmotic burden of high soil Na^+ and Cl^- (Hu and Schmidhalter, 2005).

Potassium at K1 consistently improved all morphological variables relative to K0 in both soil types (Table 4). In non-saline soil at D1, K1B0 increased SFW by 34% and RFW by 43% relative to K0B0. The K2 rate improved growth compared with K0 but was generally inferior to K1 for RDW in several drought × biochar × soil combinations, consistent with ionic antagonism at supraoptimal K supply (Sardans and Peñuelas 2021). The D × K interaction ($p < 0.001$; Table 3) confirmed that the K response was greatest under the most severe drought.

Biochar amendment (B1) enhanced RFW more consistently than SFW. At D0K0 in non-saline soil, B1 increased RFW from 128 g (B0) to 182 g (+43%) and RDW from 89.1 g to 129 g (+45%). Biochar also raised soil OM at harvest from 1.58–1.69% (B0) to 1.88–2.01% (B1) in non-saline soil and from 1.18–1.21% (B0) to 1.58–1.64% (B1) in saline soil. The three-way interaction D × K × B ($p < 0.001$ for SFW and RFW; Table 3) was the most agronomically informative result. Under D2 in non-saline soil, the K1B1 combination achieved SFW of 299 g, recovering 83% of the D0K0B0 control (321 g). In saline soil, K1B1 at D2 yielded 257 g

Table 3. Analysis of variance significance summary (F-test) for all measured response variables

Source of variation	SL	SFW	SDW	RFW	RDW	SPAD	N%	P%
Drought (D)	***	***	***	***	***	ns	***	***
Potassium (K)	***	***	***	***	***	***	***	***
Biochar (B)	***	***	***	***	***	*	***	***
Soil type (S)	***	***	***	***	***	**	***	***
D × K	***	***	***	***	**	**	**	**
D × B	**	**	**	***	**	ns	*	*
K × B	***	***	***	***	***	**	***	***
D × S	***	***	**	***	**	ns	**	**
K × S	**	**	**	**	*	ns	**	*
D × K × B	**	***	**	***	**	*	**	**
D × K × B × S	**	***	**	***	**	ns	*	*

Note: *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$; ns not significant. SL shoot length; SFW shoot fresh weight; SDW shoot dry weight; RFW root fresh weight; RDW root dry weight.

Table 4. Selected treatment means (±SE, n = 4) for key response variables in non-saline (NS) and saline (S) soil

D	K	B	SL (cm)	SFW (g)	SDW (g)	RFW (g)	SPAD	N (%)	K (%)
Non-saline soil (NS)									
D0	K0	B0	52.3	321	89.1	128	36.4	1.91	2.54
D0	K1	B0	60.7	398	109	149	42.1	2.38	3.21
D0	K1	B1	67.4	445	129	182	44.6	2.72	3.89
D1	K0	B0	42.6	249	71.3	103	35.1	1.65	2.11
D1	K1	B0	54.2	334	95.1	147	40.2	2.28	3.44
D1	K1	B1	58.9	372	105	161	41.8	2.44	3.67
D2	K0	B0	31.4	180	52.4	81.7	33.9	1.42	1.78
D2	K1	B0	46.1	265	78.3	124	39.0	2.01	3.08
D2	K1	B1	51.2	299	87.4	139	40.4	2.18	3.31
D2	K2	B1	48.7	271	81.0	128	39.1	2.05	4.12
Saline soil (S)									
D0	K0	B0	44.1	273	74.2	109	33.7	1.74	2.21
D0	K1	B0	53.4	348	96.3	143	39.1	2.29	3.19
D0	K1	B1	57.8	381	103	156	40.9	2.53	3.58
D1	K1	B1	50.2	312	88.4	140	39.2	2.29	3.28
D2	K0	B0	26.3	152	43.7	68.9	30.8	1.31	1.61
D2	K1	B0	39.8	228	66.4	109	36.8	1.89	2.89
D2	K1	B1	43.7	257	74.2	121	37.9	1.98	3.04

Note: LSD ($p \leq 0.05$): SL = 4.12 cm; SFW = 12.1 g; SDW = 4.44 g; RFW = 11.06 g; SPAD = 1.52; N% = 0.18; K% = 0.31. D drought level; K potassium rate; B biochar level; SL shoot length; SFW shoot fresh weight; SDW shoot dry weight; RFW root fresh weight.

SFW, recovering 94% of the corresponding D0K0B0 saline control (273 g). Selected treatment means are given in Table 4 and illustrated in Figures 1 and 2.

Chlorophyll content index (SPAD)

The main effect of drought on SPAD was not statistically significant (Table 3), with values ranging from 30.8 (D2K0B0, saline) to 44.6 (D0K1B1, non-saline). In contrast, the main effect of K was highly significant ($p < 0.001$): SPAD at D0 in non-saline soil increased from 36.4 (K0B0) to 42.1 (K1B0) and 44.6 (K1B1). Biochar had a small but significant ($p < 0.05$) independent positive effect. The D × K interaction for SPAD was significant ($p < 0.01$), reflecting greater relative benefit of K under drought. The four-way D × K × B × S interaction for SPAD was not significant (Table 3), indicating that chlorophyll responses to the treatment combinations were similar across soil types. Results are illustrated in Figure 3.

Effects on leaf macronutrient concentrations and soil organic matter

All measured macronutrients (N, P, K, Ca, Mg) and soil OM were significantly influenced by drought, K, biochar, and soil type, with significant D × K, K × B, and D × K × B interactions (Table 3). Leaf N was more strongly driven by K supply than by drought: in non-saline soil, increasing K from K0 to K1 raised N by 0.47 percentage points at D0 and by 0.76 percentage points at D2 (Table 4). Biochar further increased N, particularly in saline soil. Leaf P showed a parallel pattern, with K1 and B1 each independently increasing P relative to K0B0, and their combination producing the highest values under all drought levels. As expected, potassium fertilization dramatically increased leaf K concentration, confirming treatment efficacy; B1 independently maintained leaf K under drought, consistent with biochar's role in increasing soil CEC and retaining applied K^+ (Lehmann and Joseph 2015; Alkharabsheh et al. 2021).

Calcium declined markedly under drought in non-saline soil (from approximately 1.4–1.9 mg g^{-1} at D0 to 0.5–0.98 mg g^{-1} at D2), reflecting Ca's

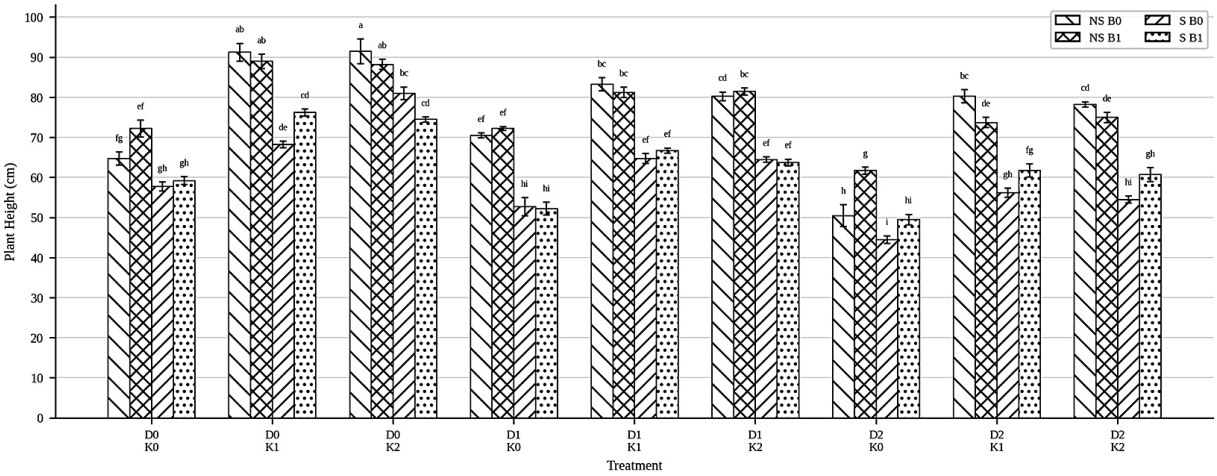

Figure 1. Plant height (cm) as influenced by drought level (D0: 100% FC; D1: 75% FC; D2: 50% FC), potassium rate (K0: 0; K1: 160; K2: 320 kg K_2SO_4 ha^{-1}), and biochar amendment (B0: 0; B1: 18 t ha^{-1}) in non-saline (NS) and saline (S) soil. Bars represent means ± SE (n = 4). Bars sharing the same lowercase letter are not significantly different (Tukey HSD, $p \leq 0.05$; all 36 treatment combinations compared simultaneously)

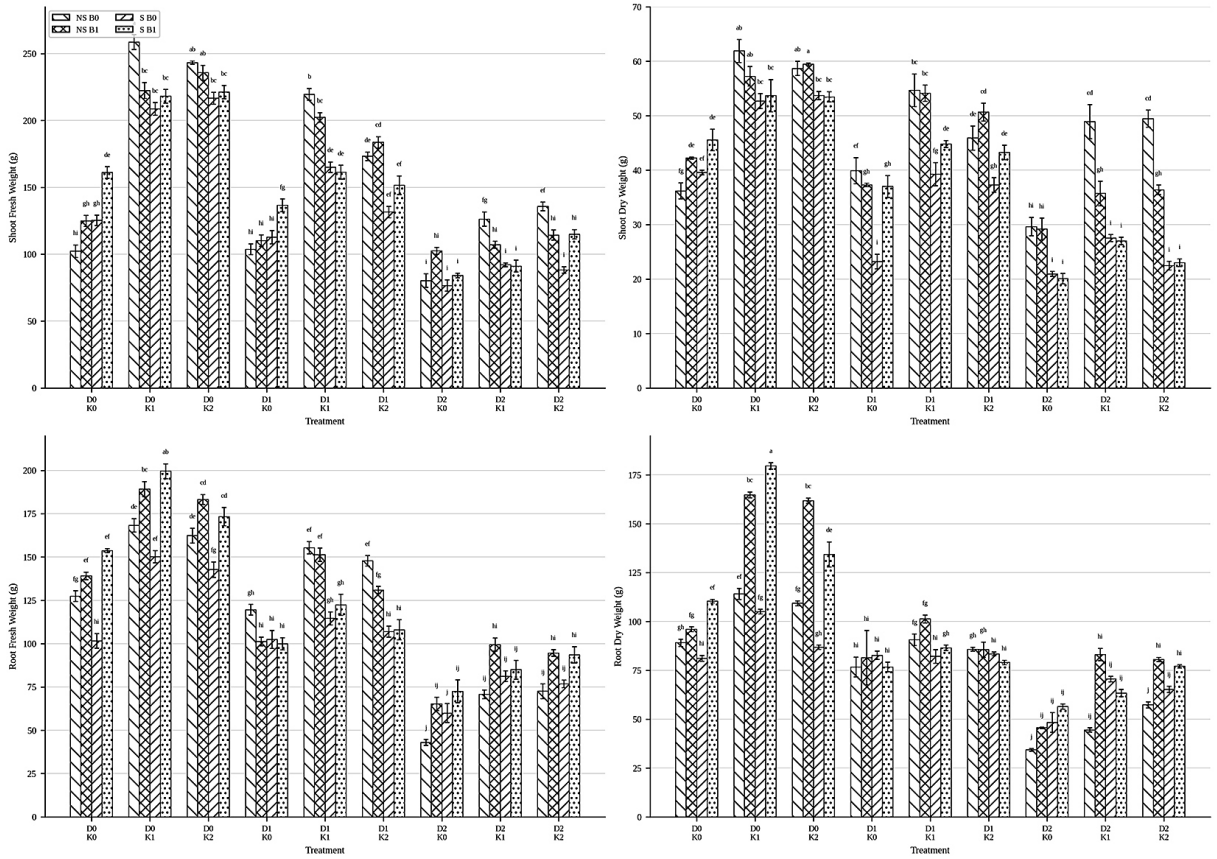

Figure 2. Shoot fresh weight (SFW, g), shoot dry weight (SDW, g), root fresh weight (RFW, g), and root dry weight (RDW, g) as influenced by drought level, potassium rate, and biochar amendment in non-saline (NS) and saline (S) soil. Bars represent means ± SE (n = 4). Bars sharing the same lowercase letter are not significantly different (Tukey HSD, $p \leq 0.05$; all 36 treatment combinations compared simultaneously)

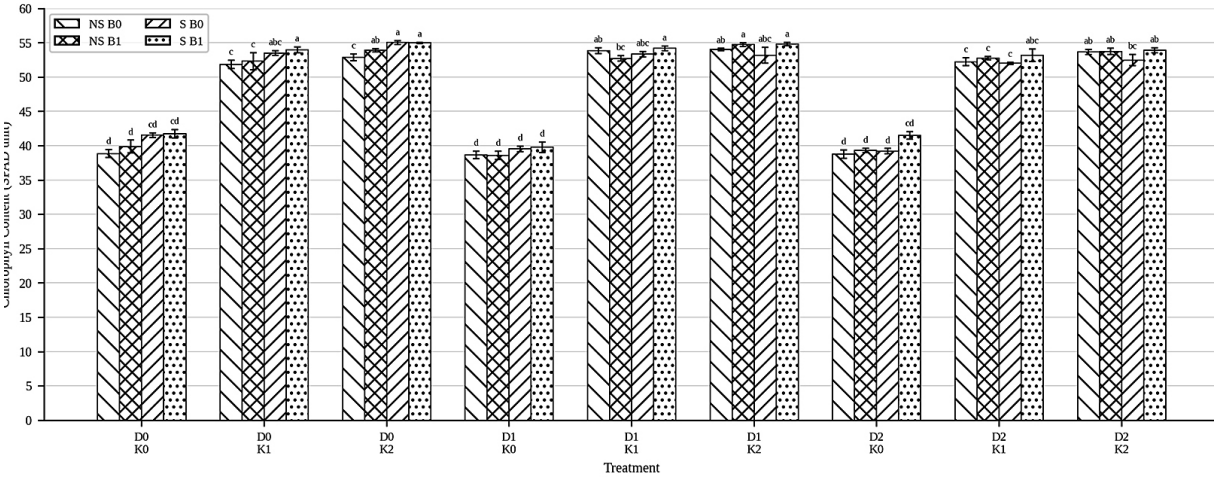

Figure 3. Chlorophyll content index (SPAD units) as influenced by drought level, potassium rate, and biochar amendment in non-saline (NS) and saline (S) soil. Bars represent means ± SE (n = 4). Bars sharing the same lowercase letter are not significantly different (Tukey HSD, $p \leq 0.05$; all 36 treatment combinations compared simultaneously)

dependence on mass flow for uptake. In saline soil, Ca concentrations showed a non-monotonic response to drought (increasing from D0 to D1, then declining at D2), possibly reflecting a concentration effect as leaf water content decreased at moderate stress followed by genuine uptake limitation at severe stress. Mg concentrations were more stable under drought than Ca in both soils, consistent with greater Mg mobility in the xylem and phloem (Hu and Schmidhalter, 2005). Soil OM increased with biochar in both soil types; neither drought level nor K rate had a consistent effect on OM over the 90-day experimental period, as expected given the dominance of stable biochar carbon over labile organic matter turnover (Idbella et al., 2024). Results are illustrated in Figure 4.

DISCUSSION

Drought and salinity effects on barley growth

The progressive reduction in shoot and root biomass with increasing drought severity is consistent with established responses of barley to water deficit and is attributed to reduced cell turgor pressure constraining cell elongation and division, downregulation of metabolic processes including photosynthesis and protein synthesis, and restricted nutrient transport to growing tissues (Anjum et al., 2011; Zahedi et al., 2025). Root fresh weight declined proportionally less than SFW under drought—particularly in biochar-amended treatments—consistent with preferential assimilate allocation to root growth to maximize water and nutrient capture under water stress (Cakmak and Rengel, 2024). The greater reductions in saline soil reflect the combined osmotic and ionic stress of high Na^+ concentrations (Hu and Schmidhalter, 2005).

The stability of SPAD values across drought levels indicates that barley cv. Rum maintained chlorophyll integrity under the tested stress regimes. This finding aligns with reports of chlorophyll maintenance in stress-tolerant barley genotypes (Al Azzawi et al., 2021). However, it is important to note that SPAD measures chlorophyll concentration per unit leaf area; if drought induced leaf rolling or reduced leaf area, total chlorophyll per plant may have declined even if the SPAD index was maintained. Gas exchange measurements, relative water content (RWC), and osmolyte quantification were not included in this study; these variables would be necessary to confirm the specific physiological mechanisms by which chlorophyll stability was maintained and are recommended for future work.

Role of potassium in mitigating drought and salinity stress

The strong positive effect of K1 on all growth and nutrient variables under drought is consistent with the established physiological functions of K. Potassium is the dominant osmoticum in guard cells, maintaining stomatal regulation and preventing

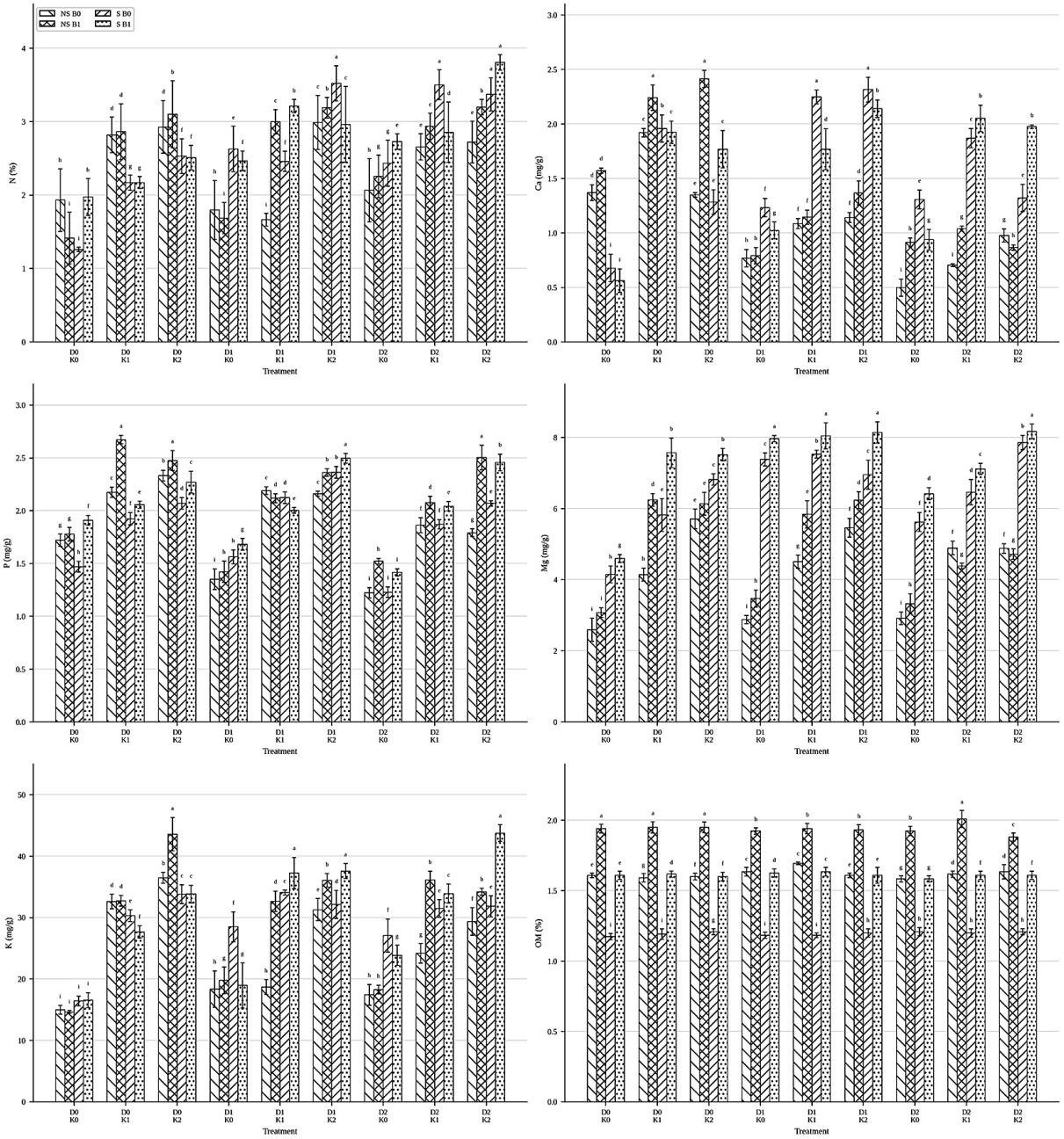

Figure 4. Leaf macronutrient concentrations (N, %; P, mg g^{-1}; K, mg g^{-1}; Ca, mg g^{-1}; Mg, mg g^{-1}) and soil organic matter (OM, %) as influenced by drought level, potassium rate, and biochar amendment in non-saline (NS) and saline (S) soil. Bars represent means ± SE (n = 4). Bars sharing the same lowercase letter are not significantly different (Tukey HSD, $p \leq 0.05$; all 36 treatment combinations compared simultaneously)

excessive water loss; it is required for phloem loading and long-distance transport of photosynthates to growing roots; and it energizes secondary active transport of nutrient ions via root membrane H^+-ATPase activity (Wang et al., 2013; Hasanuzzaman et al., 2018). The improvement in leaf N and P concentrations with K supply (Table 4) reflects these membrane-level effects and is consistent with reports of K-mediated enhancement of cross-nutrient acquisition in cereals (Ahanger et al., 2015).

The sub-optimal performance of K2 compared with K1 for root dry weight in several combinations warrants consideration. High K supply can induce antagonism with divalent cations (Ca^{2+}, Mg^{2+}) at root uptake sites, disrupting membrane integrity and osmotic balance (Sardans and Peñuelas, 2021). The observed decline in RDW at K2 relative to K1 under some drought × biochar conditions is consistent with this mechanism and suggests that 160 kg K_2SO_4 ha^{-1} is near the

optimum K rate for barley cv. Rum in the soils tested, with no agronomic benefit—and potential detriment—from higher rates. This finding has practical significance given that farmers in the Jordan Valley tend to under-apply K relative to N and P (Rusan et al. 2024; Brownlie et al. 2024).

Biochar as a soil conditioner under combined stress

The greater enhancement of RFW than SFW by biochar points to improved soil physical conditions as the primary mechanism. Biochar's porous microstructure increases plant-available water held between field capacity and permanent wilting point, and its alkaline pH and high CEC improve nutrient retention and moderate ionic stress in saline soil (Razzaghi et al., 2020; Alkharabsheh et al., 2021). The greater relative benefit of B1 for RFW at D2 than at D0, and the sustained leaf K concentrations under drought in B1 treatments, are consistent with biochar retaining applied K^+ and improving its mobility to roots at reduced soil water contents (Lehmann and Joseph, 2015). The observed OM enrichment (+0.3–0.4 percentage points in non-saline soil) reflects incorporation of stable biochar carbon and is consistent with long-term biochar persistence documented in multi-year studies (Idbella et al., 2024).

It is important to emphasize that soil water retention curves, soil microbial biomass or activity, stomatal conductance, gas exchange, RWC, osmolyte accumulation (e.g., proline), and antioxidant enzyme activities (SOD, CAT, POD) were not measured in this study. Mechanistic statements about biochar improving soil water retention, nutrient mobility, and microbial conditions are therefore presented as hypotheses supported by published evidence rather than as directly demonstrated conclusions (Rathinapriya et al., 2025; Wu et al., 2023). Future studies should integrate these measurements to fully elucidate the operative mechanisms.

Generalizability and feedstock dependence

The responses reported here are specific to the olive mill waste biochar used in this study, and their extrapolation to other biochars should be made with caution. The agronomically decisive properties of biochar—cation exchange capacity, ash content, alkalinity, and potassium content—are strongly governed by feedstock and pyrolysis temperature, and feedstock differences can even reverse the direction of the soil response, with low-ash woody biochars decreasing soil CEC while high-ash residue- or manure-derived biochars increase it (Antonangelo et al., 2024; Wu et al., 2024). The material applied here was a comparatively high-ash (27%), potassium-rich biochar produced at 350 °C; its benefits under combined drought–salinity stress are therefore most directly generalizable to other high-K, alkaline, ash-rich agro-residue biochars on calcareous soils, and should not be assumed for low-ash, low-K woody biochars or for acidic soils without dedicated validation. This reinforces the feedstock contrast noted in the Introduction, where the rice-straw, wood-chip, and poultry-manure biochars dominating the prior literature differ fundamentally from olive mill waste

Synergistic K × biochar interaction and comparison with the literature

The consistently superior performance of K1 × B1 under both drought and salinity aligns with an emerging literature documenting synergistic effects of combined K fertilization and biochar amendments. Chowdhury et al. (2024) reported that co-application of biochar and foliar K_2SO_4 in wheat increased grain yield by 43% and chlorophyll content by 125.8% relative to drought-stressed, unamended controls at the crown root initiation stage. Rahman et al. (2025) demonstrated comparable synergies in maize under three drought levels, with combined biochar and K reducing electrolytic leakage—a membrane integrity indicator—by 35–43%. El-Gamal et al. (2021) showed that biochar combined with potassium silicate improved borage yield, chlorophyll content, and water productivity under deficit irrigation. The present study extends these findings to barley under a combined drought–salinity factorial design, confirming the robustness of the K–biochar synergy across crop species and environments.

The mechanistic basis for the synergy is most parsimoniously explained as follows: biochar improves soil physical conditions (water retention, aeration, CEC), thereby amplifying the effectiveness of applied K by maintaining its mobility and bioavailability, while K independently supports the plant's internal drought tolerance mechanisms (osmotic adjustment, stomatal regulation, enzyme activation). This interpretation is consistent with findings from Rahman et al. (2025) and supported by mechanistic studies on

biochar water retention and K desorption (Razzaghi et al., 2020; Alkharabsheh et al., 2021), though direct confirmation in the present system would require soil hydraulic and K desorption measurements with and without biochar—measurements recommended for future work.

The improvements in crop performance under combined stress are consistent with biochar-induced changes in soil cation-exchange capacity (CEC) and water-holding capacity (WHC). High-K, ash-rich biochars of the type used here characteristically increase soil CEC and WHC; for example, olive-stone-pomace biochar has been reported to raise WHC by 17–35.5% and CEC by 18–163% depending on soil type, with the highest CEC (56.78 $cmol_+$ kg^{-1}) recorded for the olive-residue biochar (Ayman, 2026). A higher CEC enhances retention of exchangeable K^+ and limits Na^+ accumulation, lowering the Na^+/K^+ ratio, while greater WHC improves plant water availability under drought (Antonangelo et al., 2024; Bilias et al., 2023; Khan et al., 2024). These mechanisms provide a coherent explanation for the responses observed in the present treatments.

Practical and economic feasibility

From a practical standpoint, the 18 t ha^{-1} rate is realistic for the target production systems. The biochar is derived from solid olive mill waste (Jift), a by-product generated at large scale across the Mediterranean and Middle East without a sustainable disposal pathway; converting it to biochar offsets a waste-management burden while supplying a locally available, low-cost amendment, and on-farm or regional pyrolysis further reduces feedstock and transport costs (Marks et al., 2020). Because biochar carbon is recalcitrant, an 18 t ha^{-1} application is a one-time input whose soil-improvement benefits persist over several seasons rather than a recurring annual cost (Guan et al., 2024); its cost should therefore be amortized over its multi-year residence time, which markedly lowers the effective annual outlay. In the water-limited, salt-affected systems of the Jordan Valley, the high value of avoided yield loss under combined stress further improves the cost–benefit balance for smallholders. A formal techno-economic and life-cycle assessment nonetheless remains necessary to quantify net returns under field conditions.

Limitations

Several limitations should be acknowledged explicitly. First, this was a pot experiment measuring vegetative-stage responses only; grain yield, yield components, and water-use efficiency were not assessed, and pot-to-field scaling introduces uncertainty related to soil heterogeneity, fluctuating atmospheric conditions, and root-volume constraints. Second, mechanistic physiological variables—including gas exchange, RWC, osmolyte concentrations, antioxidant enzyme activities, and soil hydraulic properties—were not measured, preventing mechanistic conclusions beyond what the literature supports. Third, the experiment spanned a single growing season; multi-season experiments would be needed to assess biochar persistence and residual K effects over time. Fourth, no economic analysis was conducted. Fifth, the results are specific to a single high-ash olive mill waste biochar pyrolyzed at 350 °C; their transferability to biochars of contrasting feedstock or pyrolysis temperature requires dedicated validation.

CONCLUSIONS

This four-factor greenhouse pot experiment demonstrated that K fertilization at 160 kg K_2SO_4 ha^{-1} and olive mill waste biochar at 18 t ha^{-1} each independently mitigated the adverse effects of drought and salinity on barley vegetative growth and macronutrient acquisition, and that their combination (K1 × B1) was consistently superior to either amendment alone across all drought levels and both soil types. All four-way interactions (D × K × B × S) were statistically significant for most morphological and nutritional response variables, confirming that the optimal management strategy is context-dependent and cannot be determined from single-factor studies. Key findings were: (i) severe drought (50% FC) reduced SFW by 44% in non-saline soil in the absence of amendments; (ii) the K1B1 combination recovered 83% of the well-watered SFW under severe drought in non-saline soil; (iii) K at 320 kg ha^{-1} offered no consistent advantage over 160 kg ha^{-1} and reduced RDW in some combinations, indicating an optimal K rate near 160 kg ha^{-1} for this cultivar; (iv) biochar enriched soil OM by 0.3–0.4 percentage points without systematic influence from drought or K treatment; and (v) chlorophyll (SPAD) remained stable across drought levels, suggesting pigment integrity

is not a primary limitation of barley cv. Rum under the tested stress intensities. Field-scale validation including grain yield, water-use efficiency, and economic data is necessary before definitive agronomic recommendations can be made.

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