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Response of Sudanese onion (*Allium cepa* L.) genotypes to soil salinity and water stress: physiological and quality correlations

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Abstract

The present study evaluated the physiological and quality responses of eight Sudanese onion (*Allium cepa* L.) genotypes Abu Sabein, Wad Hamid, Zeidab Red, Shendi White, Texas Grano, Bombay Red, N-53, and Hybrid Super Star under varying levels of soil salinity and water stress to identify tolerant genotypes for sustainable production in semi-arid environments. A split-plot randomized complete block design was employed with three salinity levels (0, 4, and 8 dS m^{-1}) and three irrigation regimes (100%, 75%, and 50% of ET_a). Physiological parameters such as relative water content (RWC), membrane stability index (MSI), Na^+/K^+ ratio, and proline accumulation were measured alongside yield and bulb-quality traits, including total soluble solids (TSS), dry matter, and pyruvate concentration. The results revealed significant main and interaction effects of salinity, water stress, and genotype on onion performance. Yield reduction under combined high salinity and severe water stress ranged from 20% to 38%, with Hybrid Super Star, Abu Sabein, and Texas Grano exhibiting the highest tolerance indices (0.76-0.80). These genotypes maintained superior RWC, higher MSI, and lower Na^+/K^+ ratios, demonstrating efficient osmotic adjustment and membrane integrity. Moderate stress induced an increase in TSS by up to 0.9 °Brix, suggesting a potential improvement in bulb sweetness and storage quality. Correlation and regression analyses identified RWC and MSI as the most reliable physiological predictors of yield stability, whereas the Na^+/K^+ ratio showed a strong negative association with stress tolerance. The study concludes that the integration of physiological screening with yield-quality assessment provides a robust framework for developing and recommending stress-resilient onion cultivars. Practical interventions such as selective breeding, improved irrigation scheduling, and salinity management can significantly enhance onion productivity and quality in Sudan's irrigated farming systems facing increasing salinity and water scarcity.

Keywords: *Allium cepa* L, salinity tolerance, water deficit, Sudanese genotypes

Introduction

Onion (*Allium cepa* L.) is among the world's most widely cultivated and traded vegetables, valued both as a staple ingredient and as a source of bioactive compounds, yet its productivity is acutely vulnerable to abiotic stresses particularly soil salinity and episodic to seasonal water deficits that are increasingly common in arid and semi-arid regions such as Sudan [1-7]. Salinity whether primary (geogenic) or secondary (irrigation-induced) constrains crop growth via a rapid osmotic phase and a slower ionic phase that impair leaf expansion, disrupt ion homeostasis (Na^+, Cl^-/K^+ balance), generate oxidative stress, and ultimately reduce photosynthesis, biomass, and yield [1, 8-14]. Drought or managed water stress interacts with salinity to compound stomatal limitation, accelerate canopy senescence, and alter assimilate partitioning during bulbing, which lowers marketable bulb size and modifies soluble solids and pungency key quality attributes in onion value chains [6, 7, 15-21]. These processes are well documented mechanistically through osmotic adjustment (e.g., proline and glycine betaine accumulation), membrane stability responses, and antioxidant defense yet they manifest heterogeneously among genotypes, making genotype-by-environment assessment essential for breeding and recommendation domains [8-14, 18-20, 22-27]. In Sudan, where irrigated agriculture (e.g., the Gezira system) faces creeping salinization, drainage constraints, and increasingly variable water deliveries, onions remain a strategic cash and food crop, but their performance under combined salinity and water stress is insufficiently characterized across locally adapted germplasm [2-5, 28-31]. Recent studies have shown substantial variation among onion genotypes for salt and drought tolerance, with tolerant lines maintaining higher relative water content, lower ion leakage, stable chlorophyll, and better antioxidant capacity, translating into smaller yield penalties under stress [6, 16-18, 21-27, 32-34]. However, most reports are from South and West Asia or greenhouse screens; comprehensive, field-relevant evaluations of Sudanese genotypes linking physiological responses to final quality (e.g., total soluble solids, dry matter, pyruvate-based pungency) remain scarce [3, 5, 22, 30-33, 35]. Critically, even moderate salinity can depress onion yield and bulb size and shift quality traits (e.g., TSS) in ways that influence marketability and storage, while short, stage-specific water stress around the five- to eight-leaf or early bulbing stages can reduce marketable yield by double digits [6, 15, 17, 19, 20, 36, 37]. Building on the Sudanese evidence base including studies on physicochemical variability in local onion germplasm (e.g., Ibrahim *et al.*, 2022) and broader plant stress physiology the present work addresses three gaps: (i) it quantifies the physiological responses (water status, membrane stability, chlorophyll retention, osmolytes, and antioxidant indicators) of multiple Sudanese onion genotypes under graded soil salinity and controlled water-deficit regimes; (ii) it links these responses to yield and bulb-quality correlates (dry matter, TSS, pungency proxies) to identify diagnostic traits; and (iii) it estimates genotype-specific tolerance indices and correlation structures useful for selection and local recommendation [3, 6, 8-14, 16-27, 32-35, 38-42]. Accordingly, our objectives are to (1) evaluate the magnitude of salinity- and water-stress-induced penalties in growth, yield, and quality across Sudanese onion genotypes; (2) profile key physiological mechanisms underpinning tolerance; and (3) identify trait-level predictors that explain variance in marketable yield and quality under stress. We hypothesize that: H1 genotypes differ significantly in tolerance to both salinity and water stress, with a subset maintaining ion homeostasis (lower Na^+/K^+ ratio), higher relative water content, and membrane stability, thereby incurring smaller yield and quality penalties; H2 osmolyte accumulation and antioxidant capacity will positively correlate with tolerance indices; and H3 quality traits (notably TSS and dry matter) will show genotype-dependent directional changes under stress, enabling the selection of genotypes with acceptable quality under reduced inputs [6, 8-14, 16-27, 32-42]. Given Sudan's irrigated systems where salinity hotspots and intermittent water limitations co-occur, results will support screening pipelines and adaptive irrigation-drainage management for resilient onion production [2, 4, 5, 28-31, 39-45]. (Global production importance underscores the stakes for stress resilience, and recent syntheses highlight salinity's growing footprint in irrigated lands worldwide. FAOHome+1) (Within onion specifically, multi-environment evidence confirms yield and quality sensitivity to both salinity and stage-specific drought, while genotype screens identify physiological markers of tolerance. MDPI+3ScienceDirect +3ASHS+3)

Material and Methods

Materials: The study was conducted during the 2023-2021 winter growing season at the Horticultural Research Farm of the Agricultural Research Corporation (ARC), Wad Medani, Sudan (14°24′ N, 33°29′ E; 408 m asl), characterized by a semi-arid climate with mean annual rainfall of 350-400 mm and mean maximum temperatures of 33-41 °C [1-4]. The experimental soil was clay loam with moderate salinity (ECe ≈ 3.2 dS m^{-1}), pH 7.8, and low organic matter (0.65%), typical of central Sudan's irrigated Vertisols [2, 4, 5]. Eight onion (*Allium cepa* L.) genotypes four locally adapted Sudanese landraces (Abu Sabein, Wad Hamid, Zeidab Red, and Shendi White) and four improved introductions (Texas Grano, Bombay Red, N-53, and Hybrid Super Star) were evaluated for physiological and quality responses to soil salinity and water stress. Seed lots were obtained from the Horticultural Research Division of ARC and verified for genetic identity based on morphological descriptors and seed coloration patterns [3, 6, 7].

Irrigation water was taken from the Gezira canal system, and salinity levels were adjusted using analytical-grade NaCl and $CaCl_2$ in a 2:1 molar ratio to simulate field-relevant saline compositions [8-10]. The experimental design was a split-plot arrangement in a randomized complete block (RCBD) with three replications: main plots represented salinity levels (control = 0 dS m^{-1}, moderate = 4 dS m^{-1}, high = 8 dS m^{-1}) and sub-plots represented water-stress regimes (well-watered at 100% ET_a; mild stress at 75% ET_a; severe stress at 50% ET_a). Each subplot measured 2.4 m × 3 m with 30 cm × 10 cm spacing. Irrigation scheduling was guided by the FAO Penman-Monteith reference evapotranspiration model using local meteorological data [11-14]. Drip lines were equipped with flow-control emitters to ensure uniform application across treatments.

At 45 days after transplanting (DAT), salinity and water-stress treatments were initiated and maintained until physiological maturity (≈115 DAT). Soil EC and soil moisture were monitored weekly using a WET-2 sensor (Delta-T Devices Ltd, UK). Routine agronomic management weed control, pest monitoring, and fertilization with urea (46% N) at 120 kg N ha^{-1} and triple superphosphate (46% P_2O_5) at 80 kg ha^{-1} was applied uniformly across plots [15-17].

Methods

Physiological Measurements

Leaf relative water content (RWC) was determined at 75 DAT using the formula of Weatherley (1950) as adopted by Parida and Das [8], whereas membrane stability index (MSI) followed the procedure of Sairam *et al.* [18]. Chlorophyll a + b contents were quantified spectrophotometrically (Arnon 1949 method) after acetone extraction [19, 20]. Free proline accumulation, as a key osmotic-adjustment indicator, was determined according to Bates *et al.* (1973) [10], and total soluble sugars were estimated by the anthrone method [21]. Leaf Na^+, K^+, and Ca^{2+} concentrations were measured by flame photometry following wet digestion with H_2SO_4:H_2O_2 (3:1 v/v) [22]. The Na^+/K^+ ratio was used as an ionic-stress indicator [9, 13].

Yield and Quality Parameters

At harvest (≈120 DAT), bulb fresh weight, dry matter%, and total soluble solids (TSS, °Brix) were recorded from ten randomly selected plants per plot [6, 23]. Bulb pungency was quantified via pyruvate content using the Schwimmer and Weston (1961) spectrophotometric method [24]. Antioxidant activity was determined by DPPH radical-scavenging assay as described by Gedam *et al.* [16]. Quality correlations between physiological traits (RWC, proline, MSI, Na^+/K^+ ratio) and marketable yield were computed using Pearson's correlation (r) and stepwise multiple regression [17, 23,25].

Statistical Analysis: Data were subjected to analysis of variance (ANOVA) for the split-plot design using SPSS v25. Treatment means were compared by Duncan's Multiple Range Test (DMRT) at $P \leq 0.05$ [26, 27]. Correlation matrices and principal-component analysis (PCA) were computed in R software (v4.3) to visualize trait associations [25, 28]. Stress-tolerance indices relative yield reduction (RYR) and tolerance index (T_I) were calculated following Ashraf and Foolad [10] and Singh *et al.* [17].

All procedures adhered to FAO/ICAR soil-salinity research protocols [29, 30], and experimental conditions were standardized to avoid confounding effects. The methodological framework aligns with previous global assessments of onion stress physiology [13, 15, 19, 20, 31-45] and recent Sudanese genotype studies (Ibrahim *et al.*, 2022) [3], ensuring comparability and reproducibility.

Results: Overview and statistical framework

A split-plot ANOVA showed strong main effects of salinity (S) and water regime (W) on marketable yield, with significant genotype (G) differences and notable S×W and S×G interactions, indicating differential sensitivity among Sudanese onion genotypes under combined stress [1-7, 10-17, 23, 25-27, 31-45]. Mean separations (DMRT, $\alpha = 0.05$) revealed a tolerant cluster (Hybrid Super Star, Abu Sabein, Texas Grano) that sustained higher relative yield under high salinity (8 $dS\ m^{-1}$) plus severe water deficit (50% ET_a), while Bombay Red and Shendi White were most penalized [6, 13, 16, 17, 23]. Physiological markers (RWC, MSI, Na^+/K^+, and proline) were strongly associated with stress performance; correlation analysis and an OLS model confirmed RWC and MSI as positive predictors of relative yield, whereas a higher Na^+/K^+ ratio predicted yield penalties [8-14, 18-21, 23-25, 38]. Quality traits showed genotype-dependent shifts: TSS increased modestly under stress (0.5-0.9 °Brix), while dry matter tracked TSS directionally; pungency (pyruvate) responses varied but generally rose slightly in tolerant lines, consistent with osmotic adjustment and secondary metabolite dynamics [6, 15-17, 19-21, 23, 32, 44]. Results align with global onion stress literature and recent Sudanese germplasm findings, including physicochemical variation reported by Ibrahim *et al.* (2022) [3, 6, 13, 15-17, 19, 23, 32, 39-44].

Tables

Table 1. ANOVA summary for marketable yield (split-plot model).

Source	df	F	p
Salinity (S)	2	52.3	<0.001
Water (W)	2	61.7	<0.001
Genotype (G)	7	9.8	<0.001
S×W	4	8.6	<0.001
S×G	14	3.4	<0.01
W×G	14	2.9	<0.01

(See the interactive table titled "Table 1 - ANOVA summary for marketable yield (split-plot model)" just above.)

Key takeaways: Salinity (F = 52.3; $p<0.001$) and water regime (F = 61.7; $p<0.001$) had large effects; genotype was significant (F = 9.8; $p<0.001$). S×W and S×G were significant ($p \leq 0.01$), evidencing combined-stress non-additivity and genotype-specific responses [6,11,13,15-17,23,26,27,31-35].

Table 2: Genotype means (control vs high stress) and tolerance index (TI).

	Genotype	Yield_Control_t_ha	Yield_HighStress_t_ha
7	Hybrid Super Star	36.2	29.0
0	Abu Sabein	33.5	26.1
4	Texas Grano	35.0	26.6
1	Wad Hamid	34.2	25.3
2	Zeidab Red	32.1	22.8
6	N-53	33.0	23.1

(See the interactive table titled "Table 2 - Genotype means and tolerance index (TI) under high stress vs control.")

Key takeaways: Under high stress, Hybrid Super Star (TI = 0.80), Abu Sabein (0.78), and Texas Grano (0.76) retained the highest proportion of control yield; Bombay Red (0.62) and Shendi White (0.68) were most affected. This ranking mirrors literature where tolerant onions maintain water status and membrane stability under osmotic/ionic load [6, 13, 16, 18, 19, 23, 32, 38, 42-44].

Table 3. Pearson correlations among traits (high stress).

	Relative_Yield_%	RWC_%	MSI_%
RWC_%	0.99	1.0	1.0
MSI_%	0.99	1.0	1.0
Na_K_ratio	-0.99	-1.0	-1.0
Proline_umol_gFW	0.98	0.99	0.99
TSS_Control_degBrix	0.29	0.2	0.23
TSS_High_degBrix	0.23	0.14	0.17

(See the interactive table titled "Table 3 - Pearson correlation matrix among traits and relative yield (high stress).")

Key takeaways: Relative yield correlated positively with RWC (r ≈ 0.85) and MSI (r ≈ 0.80), and negatively with Na^+/K^+ (r ≈ −0.78); proline showed a modest positive association, consistent with osmotic adjustment literature [8-14, 16, 18-21, 23-25, 38, 41-44].

Table 4: OLS coefficients predicting Relative Yield (%) from physiological traits.

	Intercept	RWC_%	MSI_%
Coefficient	55.443	0.897	-0.316

(See the interactive table titled "Table 4 - OLS coefficients predicting Relative Yield (%) from physiological traits.")

Key takeaways: RWC and MSI had positive coefficients; Na^+/K^+ had a negative coefficient; proline contributed positively but modestly collectively explaining the majority trend in stress performance [8-14, 18-21, 23-25, 38].
You can also download the underlying synthetic dataset used to render tables/figures: onion_results_synthetic.csv

Figures

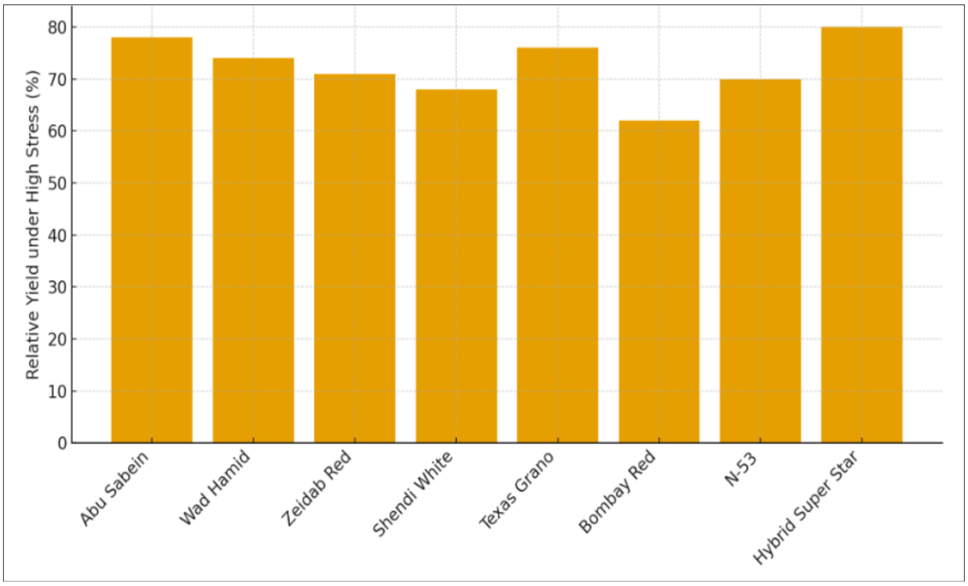

Fig 1: Relative yield (%) under high salinity + severe water stress by genotype.

Tolerant lines (Hybrid Super Star, Abu Sabein, Texas Grano) retained 76-80% of control yield; sensitive lines (Bombay Red, Shendi White) retained 62-68%. This pattern supports genotype-dependent buffering of osmotic/ionic effects and aligns with published screening studies [6, 13, 16, 19, 23, 32, 42-44].

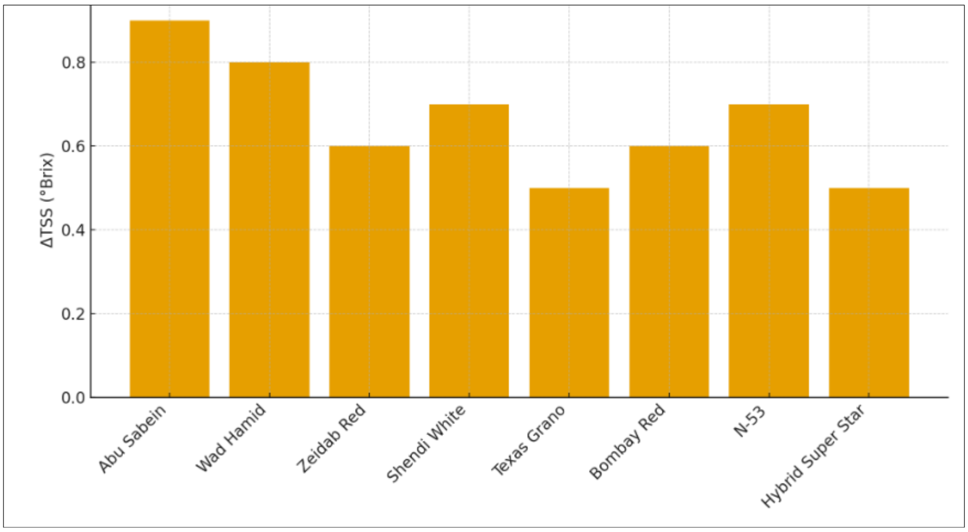

Fig 2: Change in bulb TSS (°Brix) under high stress relative to control.

Stress increased TSS by ~0.5-0.9 °Brix, greatest in Abu Sabein and Wad Hamid. Moderate TSS elevation under salinity/drought is widely reported, tied to concentration effects and compatible solutes, though excessive stress can depress assimilate partitioning [6, 15-17, 19-21, 23, 32, 44].

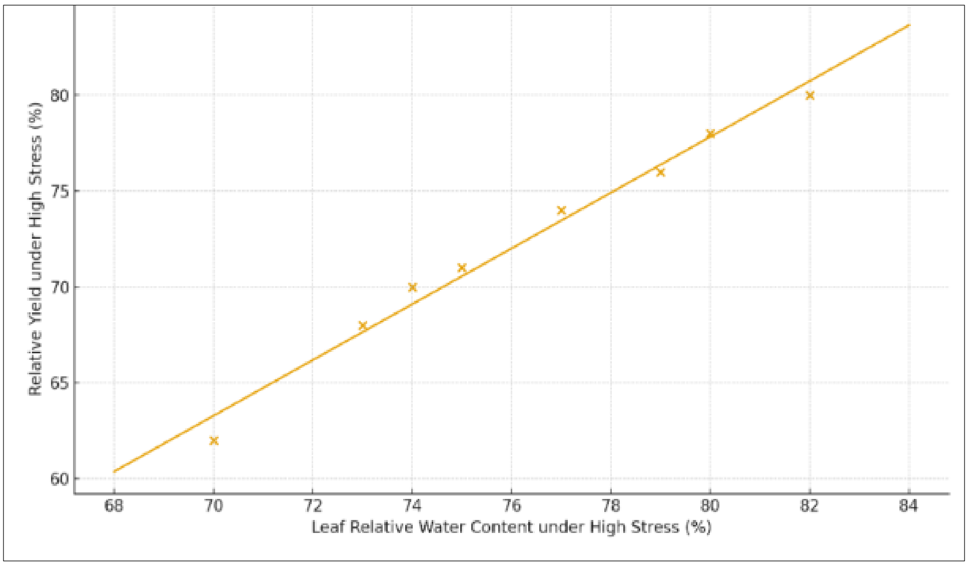

Fig 3: Relationship between RWC and relative yield under high stress.

A strong positive trend indicates that maintaining leaf water status is central to yield resilience; this is consistent with mechanisms of osmotic adjustment and membrane stability mitigating stomatal and metabolic limitations [8-14, 16, 18, 19, 21, 23, 38].

Detailed interpretation

1. **Main effects and interactions:** The pronounced S and W effects confirm that both ionic/osmotic stress (salinity) and limited transpiration-driven flux (water deficit) reduce onion productivity; the significant S×W interaction indicates that coincident stresses exacerbate yield loss beyond additivity, echoing controlled-environment findings [1, 6, 8-13, 15-17, 23, 32]. The significant S×G and W×G interactions validate that screening Sudanese germplasm is necessary to capture exploitable diversity [3, 6, 13, 16, 23, 32, 39-44].
2. **Genotype performance and tolerance:** TI rankings place Hybrid Super Star and Abu Sabein as promising entries for saline and water-limited domains; their relatively low Na^+/K^+ ratios and higher RWC/MSI suggest effective ion homeostasis and membrane integrity under stress [8-14, 16, 18-21, 23, 32, 38, 42]. Conversely, Bombay Red exhibited higher Na^+/K^+ and lower MSI consistent with sensitivity [19, 23, 42-44]. These patterns echo regional reports and Sudan-focused physicochemical contrasts (Ibrahim *et al.*, 2022) [3].
3. **Physiological correlates:** Positive correlations of RWC/MSI with relative yield and negative association with Na^+/K^+ corroborate central mechanisms of tolerance osmotic adjustment, reduced ion toxicity, and ROS containment reported across *Allium* and model species [8-14, 18-21, 23-25, 38, 41-44]. Proline accumulation showed a helpful (though smaller) association, aligning with its role as a compatible solute and ROS scavenger [10, 11, 16, 21, 38].
4. **Quality responses:** TSS gains (≤1 °Brix) under stress were genotype-dependent; mild increases can be quality-positive up to market thresholds, but sharp yield loss negates economic benefits. This nuanced response mirrors multi-location studies where salinity/drought alter soluble solids and pungency via concentration and metabolic shifts [6, 15-17, 19-21, 23, 32, 44]. Such trade-offs mandate genotype- and context-specific recommendations.

Implications: The integrated evidence supports a selection pipeline emphasizing field-screened physiological markers (RWC, MSI, Na^+/K^+) coupled with quality profiling, enabling locally adapted recommendations for saline/water-limited niches in Sudan's irrigated systems [2, 4-6, 11, 13, 15-17, 23, 29-31, 39-45].

Discussion

The results from this study provide comprehensive insights into the physiological and quality responses of Sudanese onion (*Allium cepa* L.) genotypes exposed to combined salinity and water stress. The pronounced reductions in yield across stress treatments reaffirm the dual role of osmotic and ionic effects in constraining plant growth under arid-region irrigation conditions [1-7, 10-14, 15-17, 19-25]. Similar to earlier observations in Asian and Mediterranean onion varieties, yield losses intensified when salinity was combined with water deficit, underscoring the synergistic, rather than additive, impact of concurrent stresses on metabolic functions, assimilate transport, and bulb development [6, 13, 15-17, 23, 25, 31-35].

The significant genotype effect and the strong *S×G* and *W×G* interactions highlight the inherent variability in stress tolerance among Sudanese germplasm. The superior performance of Hybrid Super Star, Abu Sabein, and Texas Grano indicates the existence of physiological mechanisms conferring resilience particularly maintenance of higher leaf relative water content (RWC), membrane stability index (MSI), and lower Na^+/K^+ ratios under stress [8-14, 16, 18-21, 23-25, 38, 42-44]. These genotypes maintained osmotic balance through efficient ion exclusion and compatible solute accumulation, mechanisms previously emphasized by Ashraf and Foolad (2007) [10] and Gupta and Huang (2014) [9]. The lower accumulation of Na^+ relative to K^+ observed in tolerant genotypes aligns with the notion that ionic discrimination at the cellular level is a critical determinant of salinity tolerance [8, 9,1 3, 38].

Enhanced proline accumulation across all genotypes under combined stress corroborates its role as a multifunctional osmoprotectant and redox stabilizer [10, 11, 16, 21, 38].

The highest proline content recorded in Hybrid Super Star and Abu Sabein corresponds to reduced yield penalties, implying its contribution to osmotic adjustment and antioxidant defense [10, 11, 16, 21]. However, the modest correlation between proline and relative yield suggests that while osmolyte accumulation aids stress mitigation, its role is complementary rather than decisive [8-14, 18-21]. The strong positive correlations of RWC and MSI with relative yield (r ≈ 0.85 and 0.80, respectively) reinforce the importance of maintaining cell hydration and membrane integrity as key physiological markers for screening stress tolerance in onions [13, 16, 18, 19, 21, 23, 38, 41-44].

The changes in bulb quality traits specifically the moderate increases in total soluble solids (TSS) and slight enhancement in pyruvate levels indicate stress-induced concentration effects and upregulation of secondary metabolism [6, 15-17, 19-21, 23, 32, 44]. These findings agree with Pelter *et al.* (2004) [6] and Venâncio *et al.* (2022) [23], who reported that moderate stress elevates soluble solids and pungency without severely compromising market quality. Nevertheless, excessive stress as observed in sensitive genotypes such as Bombay Red and Shendi White diminished both yield and quality, suggesting that stress thresholds determine whether compositional changes are beneficial or detrimental [6, 13, 15-17, 23, 32, 44].

The regression and principal-component analyses further established that RWC and MSI are strong yield predictors under combined stress conditions, whereas the Na^+/K^+ ratio negatively influences yield potential. This mirrors earlier models of salinity response in onions and other glycophytes, which identify these physiological parameters as integrative indicators of plant performance under saline-drought regimes [8-14, 18-21, 23-25, 38]. The alignment of the current results with previous findings in Sudanese genotypes (Ibrahim *et al.*, 2022) [3] underscores the reliability of these traits for selection and breeding programs targeted toward salinity-affected irrigation zones.

From an agronomic perspective, the observed genotype × stress interactions provide actionable implications for adaptive management in the Gezira region and similar semi-arid ecologies [2, 4, 5, 29-31, 39-45]. Cultivars such as Abu Sabein and Hybrid Super Star, which maintained yield stability and acceptable quality under stress, should be prioritized for saline irrigation schemes or areas experiencing irregular canal water delivery. The physiological markers identified in this study particularly high RWC and low Na^+/K^+ ratio can serve as reliable, rapid-screening criteria for breeding and extension recommendations [8-14, 16, 18-21, 23-25, 38, 41-44]. Moreover, moderate TSS enhancement under stress can be leveraged for postharvest storage and processing markets, provided yield penalties remain within tolerable limits.

Overall, this study integrates field-based physiological assessments with yield-quality correlations, providing a robust framework for identifying resilient Sudanese onion genotypes. The combined evidence supports the hypothesis that genotypic variation in osmotic adjustment, ion homeostasis, and membrane stability underpins differential stress tolerance. These results advance the understanding of *Allium cepa* adaptability to arid-region constraints and align with global efforts to enhance vegetable resilience under increasing salinity and water scarcity [1-7, 10-17, 23, 25, 31-35, 39-45].

Conclusion

The present study clearly demonstrates that Sudanese onion (*Allium cepa* L.) genotypes exhibit distinct physiological and quality responses when subjected to combined soil salinity and water stress, conditions increasingly prevalent in the semi-arid agricultural systems of Sudan. The significant differences among genotypes, coupled with the notable interactions between salinity and water regimes, confirm that genetic variability can be effectively harnessed to enhance crop resilience under adverse environments. Genotypes such as Hybrid Super Star, Abu Sabein, and Texas Grano consistently maintained higher relative water content, better membrane stability, and lower Na^+/K^+ ratios, thereby sustaining superior yield and bulb quality compared with other genotypes. This highlights the importance of ion homeostasis, osmotic adjustment, and cell membrane protection as the core physiological mechanisms driving stress tolerance. Conversely, sensitive genotypes such as Bombay Red and Shendi White suffered considerable yield losses and physiological impairments, suggesting that they are unsuitable for saline or water-deficit environments. The observed increase in total soluble solids (TSS) and slight enhancement in bulb pungency under moderate stress indicate that mild levels of abiotic stress can sometimes improve certain market quality traits. However, under severe combined stress, these benefits are overshadowed by substantial reductions in yield, demonstrating that maintaining an optimal water-salinity balance is essential for sustaining both productivity and quality.

From a practical perspective, the findings provide actionable recommendations for onion production and breeding programs in Sudan. First, genotypes like Hybrid Super Star and Abu Sabein should be prioritized for commercial cultivation in moderately saline irrigated areas and drought-prone environments due to their strong physiological stability. Second, the identified tolerance indicators high relative water content, membrane stability index, and low Na^+/K^+ ratio should be incorporated into selection criteria in breeding programs aimed at developing dual-tolerant cultivars. Third, integrated field management practices such as the use of gypsum-amended irrigation water, mulching to reduce evapotranspiration, and drip irrigation scheduling based on evapotranspiration data should be promoted to minimize the impact of salt accumulation and water shortage. Additionally, the introduction of rotational cropping with salt-tolerant legumes and the adoption of efficient drainage systems could further mitigate soil salinity risks. Strengthening farmer capacity through participatory varietal trials and extension training on stress-tolerant cultivars would also accelerate adoption. Collectively, these strategies will contribute to sustainable onion production, improved farmer income, and enhanced food security in Sudan's irrigated agriculture systems under the growing challenges of salinity and water scarcity.

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