

Integrating morpho-physiological and biochemical traits to assess drought stress and recovery tolerance in eggplant

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Abstract

Drought stress poses a significant risk to crops in future climates and represents a major challenge for maintaining global food security. In this study, we examined the morpho-physiological and biochemical responses of eggplant plants (*Solanum melongena* L.) under severe drought stress and recovery conditions. Statistical analysis revealed significant differences between treatments. Drought stress resulted in a notable reduction in shoot dry biomass by approximately 60.9% compared to control plants, while structural traits such as leaf size, root length, and internode distance remained relatively statistically unchanged. Rehydration increased the number of leaves and both shoot and root dry biomass by 29.4%, 122.2%, and 57.1%, respectively, approaching the control value. Drought stress significantly increased photosynthetic pigments (chlorophyll a, b, and carotenoids) and water status traits, including leaf water potential, stomatal conductance, and relative water content, which improved after rehydration. In terms of osmoregulation and antioxidant capacity, proline levels surged over 13 times under drought stress but dropped by 85.3% after rehydration to control levels; additionally, drought stress increased L-phenylalanine ammonia-lyase activity and polyphenol content by 34.2% and 87.8%, respectively, both of which significantly declined after rehydration. Principal component analysis revealed that eggplant plants manage drought stress through increased proline accumulation, enhanced secondary metabolism, and physiological adjustments for water management. These findings underscore the importance of developing drought-resilient crops to sustain food security amid climate challenges.

Keywords: drought stress; polyphenols; proline; recovery conditions; *Solanum melongena*; stomatal conductance

Introduction

Eggplant (*Solanum melongena* L.), a globally economically cultivated vegetable crop, offers substantial nutritional benefits due to its rich content of vitamins, phenolics, and antioxidants (Gürbüz *et al.* 2018). It belongs to the Solanaceae family and is primarily cultivated in tropical and subtropical regions worldwide, covering a cultivated area of 1.9 million hectares and yielding approximately 58 million tons (FAOSTAT 2021). In 2023, eggplant production in Morocco was reported to be approximately 61,000 tons. The production of eggplants in Morocco in 2023 produced approximately 61,000 tons of eggplants, representing a decline from its peak of 81,000 tons in 2021 (FAOSTAT, 2023). The country remains an important player in eggplant production, ranking 30th globally. As of recent reports, Morocco dedicates a cultivated area of around 2,910 hectares for eggplant farming (Maachi *et al.*, 2024). The variation in eggplant production in Morocco reflects changing agricultural patterns and challenges, particularly those related to climatic factors such as drought. These climatic stresses have significantly impacted many vegetable crops in the country, resulting in reduced yields and altered farming practices (Abdelmajid *et al.*, 2021).

Eggplants require consistent soil moisture levels to achieve optimal marketable yields. Despite eggplant being considered a moderately drought-tolerant vegetable crop, severe drought stress can significantly impact both its quality and yield (Rodan *et al.* 2020; Delfin *et al.* 2021). Persistent drought stress triggers a range of biochemical and physiological responses, resulting in changes in eggplant growth (Plazas *et al.*, 2019; Delfin *et al.* 2021; Kiran *et al.*, 2022; Akram *et al.*, 2023). It has been demonstrated that eggplant is adversely affected by drought stress in terms of plant height, total dry weight, and fruit yield (Plazas *et al.* 2019; Delfin *et al.* 2021). Under varying durations of drought stress, a decrease in transpiration rate, stomatal conductance, and photosynthesis rate of eggplant has been recorded (Sarker *et al.* 2005). The eggplant yield decreased by approximately 60% as water deficits increased from 20% to 40% of field capacity (Karam *et al.* 2011). Indeed, deficiencies in nutrient absorption and transport resulting from drought stress led to a loss in crop yield.

Drought stress and rehydration are interconnected processes in agricultural practices, with different plant varieties exhibiting varying levels of drought tolerance and recovery capabilities (Delfin *et al.* 2021). When drought stress is alleviated, crops typically show rapid growth to recover from the losses caused by water deficits. The resilience of plants plays a key role in their ability to regenerate after such stress (Chakhchar *et al.*, 2016). During the drought and rehydration phases, plants undergo significant morphological, physiological, and biochemical changes that require coordinated responses between their aboveground leaves and belowground roots (Chakhchar *et al.*, 2016, 2017, 2018a,b). While much research has focused on *S. melongena* plant responses to drought stress (Sarker *et al.*, 2005; Karam *et al.*, 2011; Plazas *et al.*, 2019), very few studies (Delfin *et al.* 2021) have investigated the specific reactions of eggplant varieties under both soil drought and rehydration.

Fluctuations in soil moisture, whether in deficit or excess, during the growth phase can adversely affect eggplant's yield and quality. In this context, this study aimed to evaluate the impact of severe drought stress followed by rehydration on the growth and physio-biochemical attributes of the commonly cultivated 'Black Beauty' eggplant variety in Morocco, during its growth phase, providing insight into the adaptive mechanisms and potential resilience of this variety under climate stress.

Materials and Methods

Plant material and growth conditions

The germination of 'Black Beauty' eggplant seeds (a variety commercialized by Atlaseeds company in Morocco) was initiated in trays filled with a 1:1 mixture of peat and compost. This variety is valued for its high fruit quality and productivity and thrives in warm climates with an optimal temperature range of 20 to 30 °C. After 28 days of sowing, sixty young plants of uniform size, measuring approximately 6 cm, were selected for

our experiment. These plants were then transplanted into plastic pots (volume 780 cm³) filled with a substrate mixture (250 g) composed of 50% peat, 25% sand, and 25% potting soil. The substrate had the following properties: pH 6.0, electrical conductivity 1.2 dS/m, nitrogen 0.5%, phosphorus 0.3%, potassium 1.0%, and organic matter 55%. Before commencing the experiment, the plants underwent regular irrigation every 48 hours for 7 days, maintaining soil moisture at the field capacity (FC) previously determined in pots without plants but containing the same substrate mixture. Indeed, the field capacity water of the substrate was gravimetrically assessed by saturating it, permitting it to drain for 48 hours, and then quantifying the volume of water retained, with four independent replicates (one pot per replicate).

During the experiment, drought stress was induced by a complete cessation of irrigation for 7 days by lowering soil moisture content to about 25% of FC, while the rehydration of the plants lasted 4 days at the end of the stress period. Substrate moisture content in the pots was determined by weighing fresh samples after plant removal (with five independent replicates), drying them at 80 °C for 72 h, and then reweighing to obtain the dry weight, using the formula: $[(\text{wet weight} - \text{dry weight}) / \text{dry weight}] \times 100$.

Treatments

The 35-days-old eggplant plants were divided into 3 blocks as follows: i- control plants normally irrigated every 48h, maintained at 90% of the FC (the added amount of water was estimated to be 85 ml, based on measurements obtained by weighing the pots using the gravimetric method), ii- plants subjected to severe drought stress (25% of FC), and iii- rehydrated plants. The experiment was carried out in a greenhouse under semi-controlled conditions (28±3 °C, 60-65% relative humidity, and natural photoperiod of approximately 12 hours of light per 24 hours) at the Higher Normal School of Marrakech (-8.05014220°/W, 31.62912560°/N, and 442.26 m altitude).

Growth traits measurement

The maximum length of the stem (LS) and root (LR), as well as the internode distance (IND) (between the 3rd and 4th node) of *S. melongena* plants, were measured using a ruler graduated in centimeters. The total number of leaves (NL) was counted. The fresh and dry biomass of the shoots (SFB and SDB) was measured by weighing using a digital precision balance in milligrams. The dry biomass of both shoots and roots (SDB and RDB) was measured after drying the fresh plant material in an oven at 70 °C for 48 hours. These measurements were conducted with four replicates per treatment (one plant per replicate).

Physiological traits measurement

Determination of leaf water potential, stomatal conductance, and relative water content

The leaf water potential (Ψ) of *S. melongena* plants was determined using a pressure chamber (SKPD 1400, Instruments Skye, Powys, United Kingdom). Stomatal conductance (g_s) was assessed using a portable porometer (Leaf Porometer LP1989, Decagon Device, Inc., Washington, USA). Measurements were taken on two leaves per plants between 10:00 and 11:00 am. Leaf relative water content (RWC) was calculated according to the formula: $\text{RWC (\%)} = (\text{FW} - \text{DW}) / (\text{SW} - \text{DW}) \times 100$, where FW, SW, and DW represent fresh weight, saturated weight (after 24 hours of rehydration in distilled water in the dark), and dry weight (after oven drying for 48 hours at 80 °C), respectively. These measurements were conducted with four replicates per treatment (one plant per replicate).

Biochemical traits measurement

Photosynthetic pigments

Chlorophyll (Chl a and Chl b) and total carotenoid (Car) contents in *S. melongena* leaves (100 mg) were quantified using 80% acetone extracts following the procedure described by Arnon (1949). The absorbance of photosynthetic pigments was recorded at wavelengths of 663 nm, 645 nm, and 440 nm, employing a digital spectrophotometer (J.P SELECTA, s.a. model VR-2000). The concentrations of Chl a, Chl

b, and Car were calculated and expressed as mg g^{-1} dry weight, utilizing the following equations: $\text{Chl a} = [12.7(\text{A}_{663}) - 2.69(\text{A}_{645})] \times (V/1000)W$, $\text{Chl b} = [22.9(\text{A}_{645}) - 4.68(\text{A}_{663})] \times (V/1000)W$, and $\text{Car} = 46.95 \times \text{A}_{440} - 0.268 \times \text{Chl (a+b)}$; where A represents the optical density, V denotes the volume (mL), and W indicates the sample weight. There were four replicates per treatment (one plant per replicate).

Organic osmolytes

For the determination of proline content (Pro), 200 mg of *S. melongena* leaf samples were homogenized with 2 mL of 40% ethanol and heated at 85 °C for 60 minutes. The homogenate was centrifuged, and proline content was quantified in the supernatant using the method outlined by Monneveux and Nemmar (1986). To the resulting supernatant (1 mL), 1 mL of glacial acetic acid and 1 mL of acid ninhydrin solution were added, and the mixture was heated for 1 hour in a boiling water bath. Subsequently, 5 mL of toluene was added to the mixture, followed by shaking to separate the upper phase. Absorbance at 528 nm was then measured, with L-proline serving as the standard. Proline concentration was expressed as mg g^{-1} DW.

The total soluble sugar (TSS) content was determined following the method outlined by Dubois *et al.* (1956). Leaf samples (100 mg) were homogenized with 80% acetone and subsequently centrifuged. The resulting supernatant (1 mL) was mixed with 1 mL of a 5% phenol solution and 5 mL of concentrated sulfuric acid. Absorbance readings were recorded at 485 nm using a digital spectrophotometer, and the concentration of soluble sugars was calculated using a standard curve generated with glucose. The total soluble sugar concentration was expressed as $\mu\text{g mg}^{-1}$ DW.

For free proline and soluble sugar content quantification, there were four replicates per treatment (one plant per replicate).

Phenylalanine ammonia-lyase activity and polyphenols content

The leaf sample (100 mg) was extracted in 50 mM Tris-HCl buffer (pH 8.0), containing 14.4 mM 2-mercaptoethanol and 1% (w/v) polyvinylpyrrolidone (PVPP), followed by centrifugation at 4 °C. The activity of L-phenylalanine ammonia-lyase (PAL) in the crude enzyme extract was determined using the method of Beaudoin-Eagan and Thorpe (1985). The assay mixture comprised 1.9 mL of 50 mM Tris-HCl buffer (pH 8.0), 0.1 mL of enzyme extract, and 1 mL of a 15 mM L-phenylalanine solution to activate the reaction. After incubating for 70 minutes at 37 °C, the reaction was terminated by adding 0.2 mL of 5 M HCl. The amount of trans-cinnamic acid produced was quantified by measuring absorbance at 290 nm, using a molar extinction coefficient of $17.4 \text{ mM}^{-1} \text{ cm}^{-1}$. PAL activity was expressed as $\text{nmol cinnamic acid mg}^{-1} \text{ protein min}^{-1}$.

For the determination of total polyphenol content (TPC), leaf samples (100 mg) were ground in 10 mL of 40% ethanol and subsequently sonicated for 30 minutes in an ultrasonic bath. After the centrifugation of the resulting homogenate total polyphenol content was estimated following the method outlined by Moutounet (1981). A volume of 2 mL of Folin-Ciocalteu reagent (diluted 10 times with distilled water) was added to 0.5 mL of the extract. After incubation for 5 minutes at room temperature, 2 mL of 7.5% Na_2CO_3 solution was added, and the mixture was homogeneously shaken and then left in the dark for 60 minutes at room temperature. Absorbance was measured at 765 nm using a spectrophotometer, and the concentration of TPC was expressed as $\text{mg of gallic acid equivalents (GAE) g}^{-1}$ DW.

For PAL activity and TPC content quantification, there were four replicates per treatment (one plant per replicate).

Statistical analysis

All experimental data were subjected to analysis of variance (ANOVA) to assess the impact of water treatment and AOS leaf spraying on the morpho-physio-biochemical traits under investigation. Statistical comparisons of means were performed at a significance level of 5% using Tukey's post hoc test. A canonical discriminant analysis (CDA), by entering all independent variables into the analysis at once, was established to

identify and distinguish discriminatory traits between different treatments. All statistical analyses were conducted using SPSS version 25 for Microsoft Windows.

Results

Statistical analysis of our findings unveiled significant differences across NL, SDB, and RDB in eggplant plants, while no significant differences were observed in LS, LR, and IND in response to the treatment factor ($p \leq 0.05$) (Table 1). Drought stress significantly decreased SDB by approximately 60.9% compared to the control, without affecting other traits. Nonetheless, the rehydration treatment significantly increased NL, SDB, and RDB, by 29.4%, 122.2%, and 57.1%, respectively, compared to the drought stress treatment. Their values were statistically similar to those observed under control conditions, particularly for the biomass traits SDB and RDB (Table 1).

Table 1. The effect of water treatment (drought stress (DS) and rehydration (R)) on growth traits in eggplant plants. (Length of the stem (LS), length of the root (LR), internode distance (IND), number of leaves (NL), shoot dry biomass (SDB), and root dry biomass (RDB))

Treatment	LS	LR	IND	NL	SDB	RDB
Control	9.25±0.65a	10.13±1.55a	0.90±0.08a	4.00±0.00b	0.46±0.09a	0.21±0.02ab
DS	9.25±0.50a	10.13±0.85a	0.95±0.06a	4.25±0.50b	0.18±0.02b	0.14±0.02b
R	10.25±0.65a	11.38±0.48a	1.00±0.00a	5.50±0.58a	0.40±0.05a	0.22±0.06a
Treatment effect	0.07	0.21	0.10	$p \leq 0.05$	$p \leq 0.05$	$p \leq 0.05$

Values (means ± S.D.) indicated by different lowercase letters are significantly different according to Tukey's test ($p \leq 0.05$)

Drought stress applied to eggplant plants significantly increased the content of Chl a and b and Car compared to control ones (128.2%, 117.4%, and 87.5%, respectively) ($p \leq 0.05$) (Table 2). However, rehydration significantly decreased the content of Chl b and Car by about 35.4% and 40.0%, respectively, compared to drought-stressed plants, without affecting the content of Chl a. This decrease resulted in statistically similar levels to those of control plants (Table 2).

Table 2. The effect of water treatment (drought stress (DS) and rehydration (R)) on chlorophyll (Chl a and Chl b) and carotenoid content in eggplant plants

Treatment	Chl a	Chl b	Car
Control	11.82±1.90b	11.45±1.79b	0.08±0.02b
DS	26.97±6.82a	24.89±6.39a	0.15±0.04a
R	20.27±3.57ab	16.09±2.44b	0.09±0.02b
Treatment effect	$p \leq 0.05$	$p \leq 0.05$	$p \leq 0.05$

Values (means ± S.D.) indicated by different lowercase letters are significantly different according to Tukey's test ($p \leq 0.05$)

Under drought stress conditions, leaf Ψ , g_s , and RWC were significantly reduced in eggplant plants by approximately 56.7%, 40.0%, and 36.6%, respectively, compared to control conditions ($p \leq 0.05$) (Figure 1). Following rehydration, a significant increase in leaf Ψ , g_s , and RWC (24.3%, 36.9%, and 47.5%, respectively) was observed compared to drought stress conditions ($p \leq 0.05$) (Figure 1). The values obtained after rehydration remain significantly lower than the control for leaf Ψ and g_s , but similar to the control for RWC.

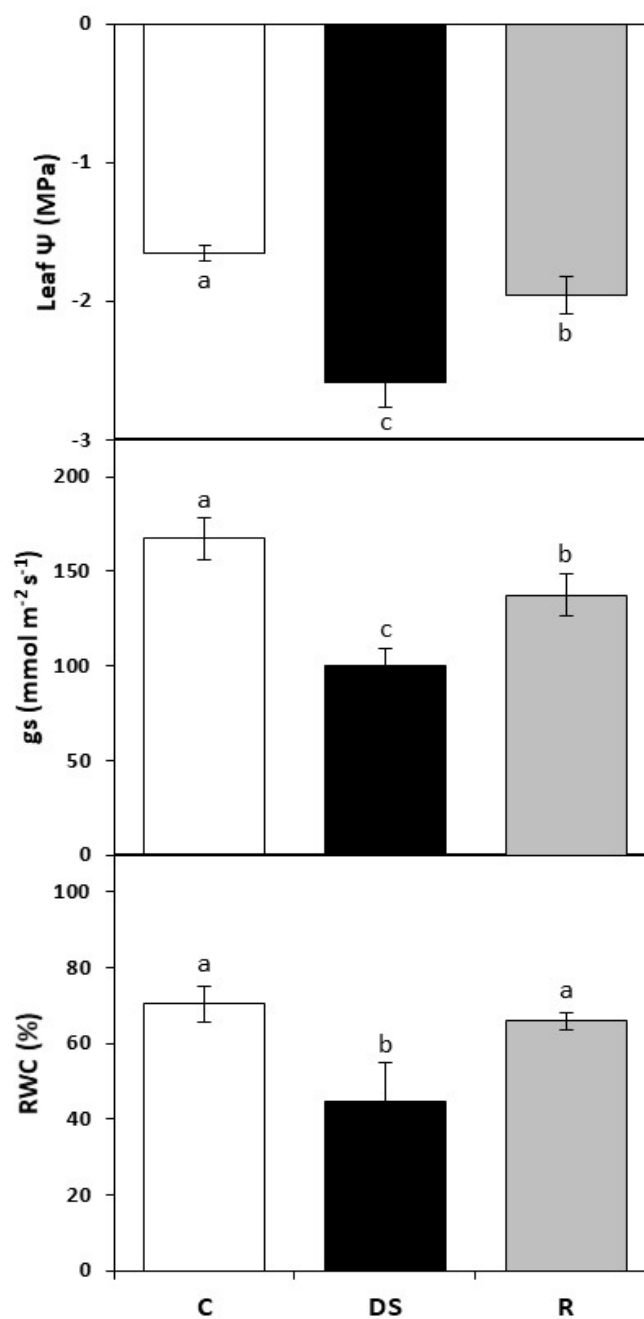


Figure 1. The effect of water treatment (drought stress (DS) and rehydration (R)) on leaf Ψ , g_s , and RWC in eggplant plants. Values (means $\pm$ S.D.) indicated by different lowercase letters are significantly different according to Tukey's test ($p \leq 0.05$)

Drought stress induced a very significant accumulation of proline (over 13 times) compared to control conditions (Figure 2), while the content of soluble sugars was not significantly affected according to the treatment factor ($p \leq 0.05$) (Figure 3). In rehydrated plants, the proline content decreased significantly by 85.3% compared to stressed plants, reaching levels statistically similar to those under control conditions ($p \leq 0.05$) (Figure 2).

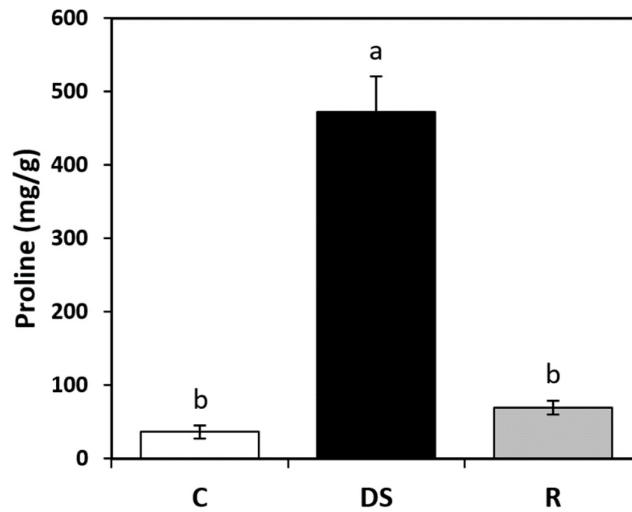


Figure 2. The effect of water treatment (drought stress (DS) and rehydration (R)) on proline content in eggplant plants. Values (means $\pm$ S.D.) indicated by different lowercase letters are significantly different according to Tukey's test ($p \leq 0.05$)

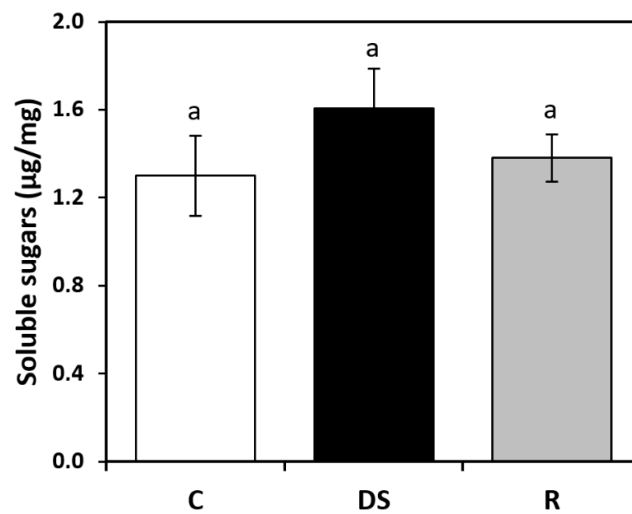


Figure 3. The combined effect of water treatment (drought stress (DS) and rehydration (R)) on soluble sugar content in eggplant plants. Values (means $\pm$ S.D.) indicated by different lowercase letters are significantly different according to Tukey's test ($p \leq 0.05$)

Compared to control conditions, drought stress significantly stimulated the activity of PAL and the accumulation of total polyphenols in eggplant plants by approximately 34.2% and 87.8% ($p \leq 0.05$) (Figure 4). After rehydration, PAL activity and polyphenol content decreased significantly by 23.9% and 42.3%, respectively, compared to the stressed conditions, and returned to levels statistically similar to those observed under control conditions.

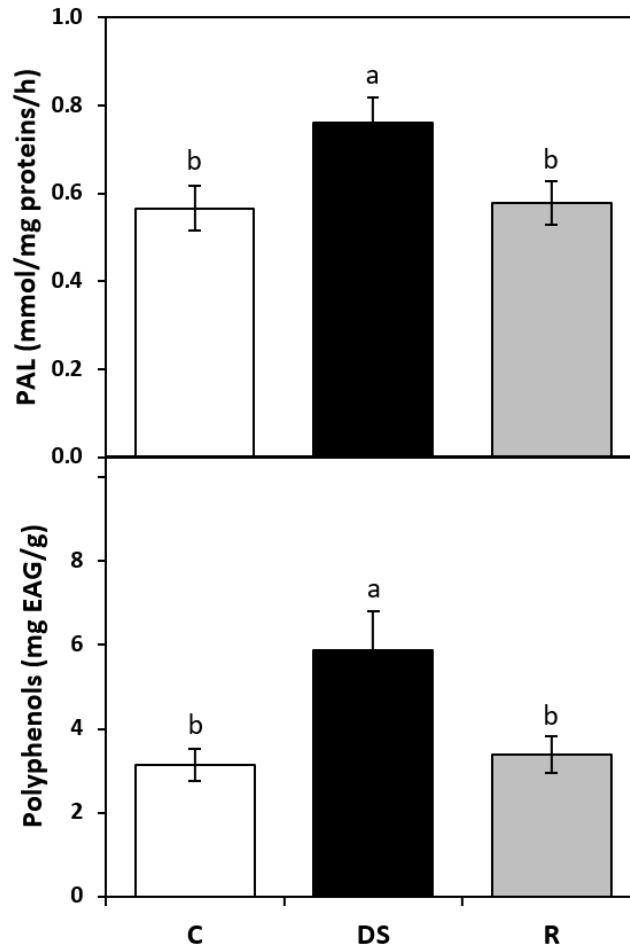


Figure 4. The effect of water treatment (drought stress (DS) and rehydration (R)) on PAL activity and polyphenols content in eggplant plants. Values (means $\pm$ S.D.) indicated by different lowercase letters are significantly different according to Tukey's test ($p \leq 0.05$)

A principal component analysis (PCA) was performed using all studied traits (16 variables) as predictors of membership in a diagnostic group. The first two principal components (PC) explained most of the variance (72.5%) (PC1 = 57.6% and PC2 = 14.9%). PCA results revealed differences between treatments investigated on eggplant plants. Regarding the component coefficient matrix and the bi-dimensional space (Fig. 6a), PC1 shows strong positive correlations, especially with Pro (0.98), polyphenols (0.90), Chl b (0.89), PAL (0.88), and Car (0.87). In contrast, it exhibits strong negative correlations with leaf Ψ (0.95), SDB (0.93) and g_s (0.90). On the other hand, PC2 shows the highest positive correlations with NL (0.87), IND (0.67), LR (0.62), and LS (0.59), while the highest negative correlations for PC2 are with leaf Ψ and g_s (0.18 for both). These first two PC achieved a good separation among the examined treatments. The PCA projection (Fig. 6b) reveals a clear separation between the drought stress treatment and both the control and rehydration treatments along PC1, while the rehydration treatment is distinctly separated from the control and drought stress treatments along PC2. Corroborating the ANOVA results, PCA revealed that eggplant plants respond to drought stress by activating osmoregulatory mechanisms, accumulating high concentrations of proline, stimulating secondary metabolism, and modulating physiological traits that control their water status.

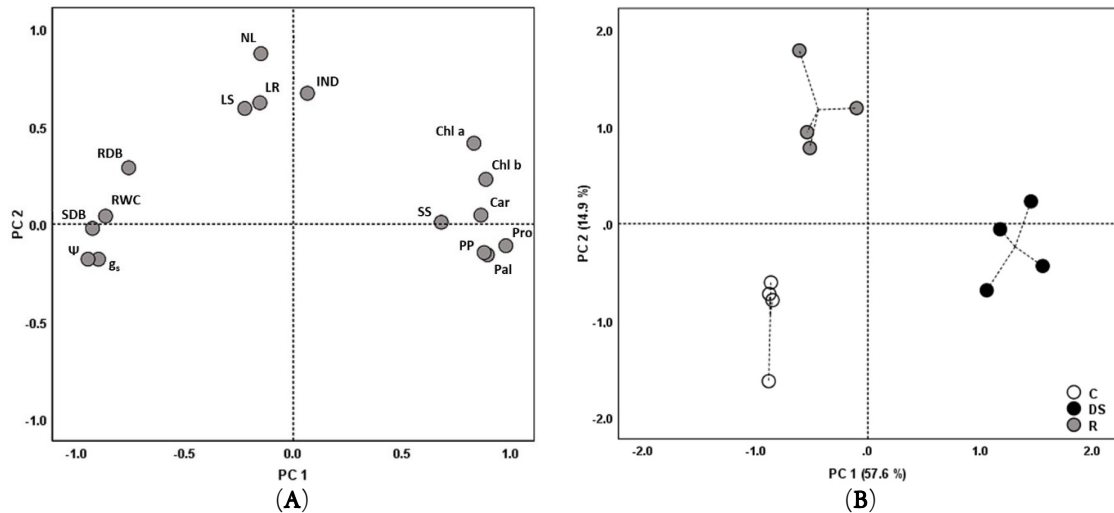


Figure 5. 2D Scatterplot PCA showing the distribution of all studied parameters (A) and examined treatments (B) (Control (C), drought stress (DS), and rehydration (R),) according to the two main principal component gradients, which are correlated with growth, physiological, and biochemical traits in eggplant plants

Discussion

Our study examined the physiological, biochemical, and growth responses of eggplant plants subjected to drought stress followed by rehydration. The results highlight the complex interactions between drought stress and rehydration, revealing both adaptive and maladaptive responses within eggplant plants. Significant differences in key growth traits, including the number of leaves and shoot and root dry biomass in response to treatments were recorded between treatments, while structural traits such as leaf size, root length, and internode distance remained relatively statistically unchanged. These findings suggest that drought stress primarily affects biomass production rather than structural attributes, which aligns with recent studies by Delfin *et al.*, (2021), Semida *et al.*, (2021), and Kiran *et al.*, (2022), who observed similar trends in *S. melongena* genotypes. Drought stress led to a significant reduction in shoot dry biomass by 61.2% compared to control plants, consistent with findings from Plazas *et al.*, (2019) who documented comparable reductions in four eggplant varieties. Drought stress negatively affects cell division and growth by causing turgor loss, reducing enzyme activity, and limiting energy supply (Qi and Zhang, 2020). As a result of competition for water and nutrients between roots and shoots, shoot biomass are decreased (Plazas *et al.*, 2019). However, the remarkable recovery ability of the studied eggplant variety through re-watering after drought stress restored both shoot and root dry biomass affected by drought to levels comparable to those of the control plants. In contrast to our results, Delfin *et al.* (2021) found that these growth traits did not fully recover to the levels observed in control eggplant plants after re-watering.

Moreover, drought stress causes various physiologic and biochemical effects in plants (Chakhchar *et al.*, 2018a). Our results demonstrated significant reductions in leaf water potential, stomatal conductance, and relative water content under drought stress conditions. Comparable responses were observed in other eggplant varieties, indicating a notable decrease in these physiological traits, which subsequently led to a reduction in the photosynthetic rate (El-Sayed *et al.*, 2021; Semida *et al.*, 2021; Hannachi *et al.*, 2023; Opoku *et al.*, 2024). Indeed, numerous studies showed that eggplants exposed to drought had lower photosynthetic pigments such as Chl a, Chl b, and carotenoid contents (Mibei *et al.*, 2017; Plazas *et al.*, 2019; Alabdallah *et al.*, 2021; Akram *et al.*, 2023). Unexpectedly, drought stress led to an increase in chlorophyll and carotenoid contents in our study, likely due to enhanced chloroplast production to support assimilation and as a compensatory strategy

for photosynthetic limitations. This increase may also result from the protective effects of antioxidants and osmolytes, which help maintain chlorophyll levels despite minor chloroplast damage (Kiran *et al.*, 2022). In addition to their primary role as accessory photosynthetic pigments and precursors of plant hormones, carotenoids also serve to protect chlorophyll from harmful photooxidation. They exhibit significant radical scavenging and singlet oxygen-quenching abilities, enhancing the overall photoprotection of plants (Edge and Truscott, 2018). Comparable responses in chlorophyll and carotenoid content have been documented in other Turkish eggplant varieties (Kiran *et al.*, 2022). Following rehydration, improvements in water status traits were observed, indicating that eggplant plants adjusted to optimal hydration levels after stress. However, this adjustment was accompanied by a decrease in photosynthetic pigments. The reduction in chlorophyll and carotenoid content may reflect a return to normal physiological functioning, as the plant no longer needs to upregulate pigment production to compensate for drought-induced photosynthetic limitations.

Despite their accumulation generally not interfering with normal cellular metabolism, osmolytes and antioxidants play a crucial role in maintaining osmotic regulation and providing protection against oxidative stress. In stressed eggplants, concentrations of proline and polyphenols were significantly enhanced under drought stress. Proline, a typical compatible solute in plants, has been reported to increase markedly in various species, including *S. melongena*, during environmental stresses like drought stress (Plazas *et al.*, 2019; Kiran *et al.*, 2022; Akram *et al.*, 2023; Flores-Saavedra *et al.*, 2024).

Our results suggest that higher proline concentrations may be associated with improved drought adaptation in *S. melongena*. Several studies have highlighted proline's essential role in osmotic adjustment and the protection of cellular structures in various eggplant varieties and cultivars, correlating increased levels of this osmolyte with the maintenance of photosynthetic activity under drought conditions (Plazas *et al.*, 2019; Kiran *et al.*, 2022; Akram *et al.*, 2023). Polyphenols are potent antioxidants found in eggplant, which is classified as a functional food (Niño-Medina *et al.*, 2017). Our results revealed a significant accumulation of leaf polyphenols in eggplant plants under drought stress compared to well-watered plants. The activation of phenylalanine ammonia-lyase (PAL) under drought stress in eggplant was associated with increased polyphenol accumulation. It catalyzes the first step in the metabolic pathway of flavonoids and other phenolic compounds, leading to an increased accumulation of polyphenols in response to various environmental stresses, such as drought (Chakhchar *et al.*, 2015). This suggests that regulating PAL is essential for plant defense and adaptation, as it enhances the synthesis of polyphenolic compounds vital for coping with water-limiting conditions. Polyphenols are part of the secondary reactive oxygen species scavenging systems that are activated only when the activity of antioxidant enzymes declines under severe stress (Fini *et al.*, 2011; Lv *et al.*, 2021). Corroborating our results, other authors have also reported a significant accumulation of polyphenols in various eggplant varieties under drought stress (Plazas *et al.*, 2019), while others have noted a decrease in different varieties of the same species (Kiran *et al.*, 2022). It is noteworthy that multiple authors have emphasized that intraspecific variations in eggplant responses differ among specific varieties and cultivars (Plazas *et al.*, 2019; Akram *et al.*, 2023; Flores-Saavedra *et al.*, 2024).

Upon rehydration, the marked decrease in proline concentration further corroborates the reversibility of osmotic stress in eggplant, as proline levels returned to baseline values similar to those observed in control plants. Additionally, the rehydration treatment led to a reduction in polyphenol content, suggesting that once the stress is alleviated, the plant may downregulate the biosynthesis of secondary metabolites that were elevated under stress conditions (Chakhchar *et al.*, 2016).

Our comparison of water-stressed and rehydrated plants against control ones, conducted through PCA, revealed, consistent with findings in *S. melongena*, particularly under drought stress (Plazas *et al.*, 2019; Flores-Saavedra *et al.*, 2024), a clear impact of drought stress treatment on the morphological, physiological, and biochemical responses of eggplant to drought. Strong correlations were observed between photosynthetic pigments and traits related to osmotic regulation (proline) and antioxidant defense (polyphenols). These differences could be leveraged to enhance our understanding of drought tolerance mechanisms, contributing to the selection of more drought-resistant eggplant varieties.

Conclusion

Drought stress triggered a range of physiological and biochemical changes in eggplant, including the accumulation of osmoprotectants like proline and enhanced secondary metabolism. Significant reduction in shoot dry biomass while increasing chlorophyll and carotenoid content, which effectively restored after rehydration to levels similar to control conditions. Although drought stress impaired leaf water potential, stomatal conductance, and relative water content, these parameters improved after rehydration. PCA indicated that eggplant plants respond to drought stress by activating osmoregulation, accumulating proline, enhancing secondary metabolism, and adjusting physiological traits to manage water status. Our results offer valuable insights into the physiological and biochemical responses of eggplant to drought stress. Future investigations should evaluate additional traits and a broader range of Moroccan eggplant genotypes from arid habitats to identify promising materials for breeding, including the assessment of both tolerant and susceptible cultivars that could serve as controls in this crop.

Authors' Contributions

Conceptualisation: AC, MA, KA, MAZ, AB, AC and REB; methodology: KA, MAZ, AB, AC and REB; software: AC; validation: MA, AFM and CEM; formal analysis: AC; investigation: AC, MA, KA, MAZ, AB, AC and REB; resources: MA, AFM and CEM; data curation: AC; writing – original draft preparation: AC, MA, KA, MAZ, AB, AC and REB; writing – review and editing: AC.

All authors read and approved the final manuscript.

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Conflict of Interests

The authors declare that there are no conflicts of interest related to this article.

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