DOI: https://doi.org/10.70749/ijbr.v3i6.1629

INDUS JOURNAL OF BIOSCIENCE RESEARCH
https://induspublishers.com/IJBR
ISSN: 2960-2793/ 2960-2807

Effect of Foliar by Applied Moringa Leaf Extract on Tomato Growth Performance under Drought Stress

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ARTICLE INFO

Keywords: Foliar spray, Drought Stress, Plant Yield, Moringa leaf extract (MLE), Tomato growth

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Declaration
Authors' Contribution: All authors equally contributed to the study and approved the final manuscript.

Conflict of Interest: No conflict of interest.

Funding: No funding received by the authors.

Article History
Received: 17-03-2025 Revised: 12-05-2025
Accepted: 27-05-2025 Published: 21-06-2025

ABSTRACT

Among stresses, drought is a fatal that causes threats to crops. Drought stress is a significant constraining element in tomato manufacturing, affecting plant development, yield, and fruit excellence. Therefore, scientists have been utilizing numerous tactics to mitigate the damaging consequences of water deficit. Plant growth promoters such as extract from moringa leaves are often utilized exogenously to vegetation to promote their resistance to numerous abiotic stresses. Three varying dosages of extract from moringa leaves 0%, 3% as well 6% were sprayed to the tomato (*Solanum lycopercium*) crop. The experiment was CRD designed with three replications. Drought (45% FC) was applied to determine the toxic impact on growth variables and the physiology of tomato. The data noted during the study was assessed for variance by utilizing CO_ STAT software. Results demonstrated that drought diminished all growth metrics and ion contents. During drought conditions, moringa-treated plants had improved growth factors and physiochemical attributes such as soluble sugar, flavonoids, anthocyanin, ascorbic acid, chlorophyll, and ion contents. MLE application increased proportionate amounts of proline and water, suggesting improved water retention and stress tolerance. Increased antioxidant enzyme activity in treated plants also indicated a bolstered defense mechanism against drought-induced oxidative stress. Foliar application of Moringa leaf extract demonstrates promising potential as a sustainable agronomic method to enhance tomato expansion and stress resilience under drought conditions. The 6% moringa leaf extract had a greater impact on all measured variables. It was stated that Leaf extract from moringa can be utilized as a development promoter because this can optimize the morpho-physiological attributes as well as biochemical features of tomato by lessening the destructive effects of drought. It was stated that extract from moringa leaves can be utilized as a growth-promoting agent because it can optimize the morpho-physiological attributes as well as biochemical features of tomato by lessening the destructive effects of drought.

INTRODUCTION

Climate change and the resultant global warming have precipitated a decline in water resources worldwide, exerting significant repercussions on agricultural productivity (Abbasi et al., 2020). Diminished soil water availability impinges upon the internal water status of plants, thereby impeding their both biological and physiological meanings. In spite of the financial significance of tomatoes, they are prone to the effects of drought, particularly during their flowering and fruit growth stages (Jangid & Dwivedi, 2016), leading to compromised germination of seeds, attenuated plant growth, and diminished fruit production (Liu et al., 2017).Vegetables play a pivotal role in human nutrition and health by furnishing energetic vitamins, minerals, fibers and antioxidants (Dalal et al., 2006).Drought stress exerts adverse impacts on vegetable yield and quality (Maggio et al., 2005).Prolonged drought periods can inflict enduring harm on plants, encompassing disruptions in stem and root development, alongside reductions in leaf number and width. Moreover, diminished water potential within plant cells can impede developmental progress. Numerous studies corroborate that drought stress compromises plant growth, metabolic processes, and photosynthetic attributes (Ors & Suarez, 2017). Tomato (*Solanum lycopersicum* L.) stands as a preeminent Fruit and Vegetable of considerable global economic significance (Jangid & Dwivedi, 2016). However, it is markedly susceptible to drought stress (Saadi et al., 2015), as evidenced by its pronounced results factor of response under water pressure conditions (Kamanga & Ndakidemi, 2022). Tomato (*Solanum lycopersicum* L.) ranks as the secondary grain-free food crop globally, trailing only behind potatoes (Gondal et al., 2019). Global manufacturing of tomatoes is valued at a staggering 161.7 million metric tons, or almost 59 billion USD in value (Lee & Kennedy, 2020). Within Pakistan, tomato manufacturing holds the 34th position between nations worldwide, with an annual assembly exceeding 572,837 tons (Anjum et al., 2020).Photosynthesis, a highly regulated and sensitive physiological trait, is significantly impacted by drought stress (Galmes et al., 2011).The down control over photosynthesis often engenders the generation of oxygen species that are reactive (ROS), culminating in photo inhibitory impairment to photosynthetic apparatuses and cellular membranes (Kamanga et al., 2018).

Several methodologies and parameters for assessing drought tolerance have been devised (Waheed, 2014). Moringa is revered as a therapeutic plant owing to its repertoire of bioactive compounds, which may deliberate antibacterial, anti-inflammatory and antioxidative possessions. Moringa leaves harbor a diverse array of bioactive compounds encompassing vitamins A, thiamine, riboflavin, niacin, ascorbic acid, carotenoids (Leone et al., 2015). The admiration of MLE as a biostimulant has surged owing to its efficacy in ameliorating environmental stressors impeding growth of plant, such as salinity, scarcity, heavy metals and heat stress (Batool et al., 2020). This research endeavors to scrutinize the structure and various application modalities of MLE, alongside its affirmative outcomes in reducing the consequences of drought stress. Moringa is utilized in emerging economies as a micronutrient source, natural pesticide, and metabolic conditioner to combat widespread disorders. MLE, enriched with hormones, amino acids, and various beneficial compounds, exhibits promise as a plant expansion enhancer. Treatment with MLE results in a noteworthy evolution in growth parameters, Soil-Plant Analysis Development (SPAD) and photosynthetic pigments, values related to the control group. The study results will support tomato productivity and yield in drought-stressed environments.

MATERIALS AND METHODS

Experimental Site and Design

A pot trial was accomplished at the Old Botanical Garden, University of Agriculture, Faisalabad, using completely randomized design on 12th February, 2024.

Experimental Setup

Five plants of two different tomato varieties (Nadir and Naqib) were planted in each plastic pots comprising 7kg sieved soil. After one week, each pot of plants was kept with thinning. Basically, it was two factor study; factor A: drought stress ($FC_{1=}$100%FC, FC=45%FC) and factor B: applying moringa leaf extract topically at (0%,3%, 6%). The drought stress related treatment imposition was performed at thirty days after germination whereas moringa leaf extract was sprayed after one week of DS imposition according to set treatments.

Morphological attributes, including root and shoot length, fresh and dry weight of shoots, fresh and dry weight of roots, and number of leaves per plant and physiochemical parameters such as chlorophyll components, carotenoids, flavonoids, ascorbic acid anthocyanin, and ion analysis were assessed post-harvest.

Morphological and Yield Related Traits

A measuring rod was used to measure the length of the shoots and roots at maturity. An electrical balance was used to calculate the fresh weight of the shoot and root. To control the dry weight, plant models were subsequently oven-dried for 72h at 65%. Each plant's leaves were hand counted. The number of vegetative and floral shoots on each plant were counted.

Evaluation of Biochemical Parameters

Chlorophyll Pigments: Photosynthetic pigments were identified using the (Zdravković et al., 2013) recommended approach. This involved using a mortar and pestle to crush 0.1 g of fresh leaves from the working sample in 2 mL of 80% acetone before adding them to the test tubes. A spectrophotometer (UV-3802, UNIC, and Shanghai, China) was used to detect the absorbance of carotenoid, chlorophyll a, and b at 663, 645, and 480 nm, respectively. Utilizing the subsequent formulas, determine the concentrations of carotenoids, chlorophyll a, and chlorophyll b.

Chl. a (mg mL-1) = [12.7 (OD 663) - 2.69 (OD645)] × V/1000 × W

Chl. b (mg mL-1) = [22.9 (OD 645) - 4.68 (OD663)] × V/1000 W

Where V= Volume of the extract (mL)

Weight of the fresh leaf tissue (g)

Carotenoids = [(OD 480) + 0.114 (OD 663)-0.638 (OD645)]

E 100% Cm = 2500

Carotenoids (g mL-1) = Acar / Em100% × 100

Anthocyanins: A fresh leaf sample weighing 0.1 g was grounded in 2 mL of acidified methanol that was organized using 1 ml hydrochloric acid and 99 ml methanol (STRACK & WRAY, 1989). The pulverized material was then put in test tubes and heated in a water bath at 50 degrees Celsius for 60min. This combination was then filtered, and readings at 535 nm were recorded using a spectrophotometer.

Flavonoids: The flavonoid content was resolute following the process of (Zhishen et al., 1999). To measure the flavonoid content, 0.1 gram of fresh leaf material was powdered in two milliliters of 80% acetone. Each test tube received a milliliter of the extract. Four milliliters of distillation water were then added. Six milliliters of 5% $NaNO_2$ and half a milliliter of 10% $AlCl_3$ were added to the mixture after it had been left at room temperature for five minutes. The mixture was then diluted by adding 2.4 ml of distilled water and 2 ml of 1M NaOH solution. At 510 nm, the values were recorded.

Ascorbic Acid: The ascorbic acid contents were resolute using the (Morales-Contreras et al., 2018) methodology. 2 milliliters of 6% TCA were used to grind 0.1 grams of fresh leaf material. The test tube then filled with one milliliter of extract. After adding one drop of 10% thiourea and one milliliter of 2% dinitrophenyl hydrazine, the mixture was boiled for fifteen minutes at 95°C.After letting the liquid chill on ice, 2.5 milliliters of 80% sulfuric acid were added. The absorbance at which the data were collected was 530 nm.

Ion analysis

Determination of K^+, Ca^{+2} and Na^+

Sodium, calcium and potassium configuration were analyzed by utilizing Atomic Absorption Spectrum. Readings were taken from a flame photometer by operating calcium, potassium and sodium standard. This method for determining calcium and potassium was presented by (Mphahlele et al., 2020).

Statistical Analysis

The collected data for growth, morphological, physio-chemical analysis was statically analyzed using statistics 8.1 and their mean value was computed at 5% probability level.

RESULTS AND DISCUSSION

Shoot Fresh Weight

Statistical analysis highlighted a momentous interaction ($P < 0.05$) amid varying levels of foliar spray and drought stress treatments on the Relative Fresh Weight (RFW) of shoots. According to the bar graph, the foliar spray significantly influenced the RFW. Drought stress reduced the RFW in plants, but the application of foliar spray improved the RFW in plants under stress as well as those not compared to control plants (Anwar et al., 2021). As a result, the results demonstrated that a 6% concentration of foliar spray had the most substantial impact on increasing RFW, followed by 3% and 0% concentrations. Specifically, the trend in increasing RFW was 6% > 3% > 0% foliar spray. This pattern was consistent across both 'nadir' and 'naqib' varieties under different water availability conditions (Mukimuddin, 2024), as shown in the bar graph (Fig. 1).

Root Fresh Weight

Statistical analysis highlighted a momentous interaction ($P > 0.05$) amid varying levels of foliar spray and drought stress treatments on the Relative Fresh Weight (RFW) of roots. According to the bar graph, the foliar spray significantly influenced the RFW. Drought stress reduced the RFW in plants, but the application of foliar spray improved the RFW in plants under stress as well as those not compared to control plants (Zhang et al., 2016). As a result, the results demonstrated that a 6% concentration of foliar spray had the most substantial impact on increasing RFW, followed by 3% and 0% concentrations. Specifically, the trend in increasing RFW was 6% > 3% > 0% foliar spray. This pattern was consistent across both 'nadir' and 'naqib' varieties under different water availability conditions (Pal et al., 2015), as shown in the bar graph (Fig. 2).

Shoot Dry Weight

Statistical analysis highlighted momentous interaction ($P > 0.01$) amid varying levels of foliar spray and drought stress treatments on the Relative Dry Weight (RDW) of shoots. According to the bar graph, the foliar spray significantly influenced the RDW. Drought stress reduced the RDW in plants, but the application of foliar spray improved the RDW in plants under stress as well as those not compared to control plants (Mannan et al., 2022). As a result, the results demonstrated that a 6% concentration of foliar spray had the most substantial impact on increasing RDW, followed by 3% and 0% concentrations. Specifically, the trend in increasing RDW was 6% > 3% > 0% foliar spray. This pattern was consistent across both 'nadir' and 'naqib' varieties under different water availability conditions (Alghamdi et al., 2022), as shown in the bar graph (Fig. 3).

Root Dry Weight

Statistical analysis opened a momentous interaction ($P > 0.05$) between varying levels of foliar spray and drought stress treatments on the Relative Dry Weight of roots. According to the bar graph, the foliar spray significantly influenced the RDW. Drought stress reduced the RDW in plants, but the application of foliar spray improved the RDW in plants under stress as well as those not compared to control plants (Alghamdi et al., 2022). Overall, the analysis demonstrated that a 6% concentration of foliar spray had the most substantial impact on increasing RDW, followed by 3% and 0% concentrations. Specifically, the trend in increasing RDW was 6% > 3% > 0% foliar spray. This pattern was consistent across both 'nadir' and 'naqib' varieties under different water availability conditions (Sardar et al., 2021), as shown in the bar graph (Fig. 4).

Shoot Length

Statistical analysis highlighted a momentous interaction ($P < 0.01$) amid varying levels of foliar spray and drought stress treatments on the Relative shoot length (RSL). According to the bar graph, the foliar spray significantly influenced the RSL. Drought stress reduced the RSL in plants, but the application of foliar spray improved the RSL in plants under stress as well as those not compared to control plants (Pourghasemian et al., 2020). As a result, the results demonstrated that a 6% concentration of foliar spray had the most substantial impact on increasing RSL, followed by 3% and 0% concentrations. Specifically, the trend in increasing RSL was 6% > 3% > 0% foliar spray. This pattern was consistent across both 'nadir' and 'naqib' varieties under different water availability conditions (Laane, 2018) as shown in the bar graph (Fig. 5).

Root Length

Statistical analysis indicated a non-significant interaction ($P > 0.01$) between various foliar spray concentrations and water stress treatments. Graphical data indicated that foliar spray had a significant upshot on root length. Root length was notably lower in drought-treated plants, but foliar spray improved the root length of all plants under stress as well as those not compared to the control (Tayyab et al., 2020). As a result, the results demonstrated that a 6% concentration of foliar spray had the most substantial impact on increasing root length, followed by 3% and 0% concentrations. Specifically, the trend in increasing root length was 6% > 3% > 0% foliar spray. This pattern was consistent across both 'nadir' and 'naqib' varieties under different water availability conditions (Ullah et al., 2023), as shown in the bar graph (Fig. 6).

Number of Leaves Per Plant

Statistical data showed a momentous interaction ($P > 0.01$) between various foliar spray concentrations and water stress treatments. Graphical data indicated that foliar spray had a momentous influence on number of leaves. Number of leaves was notably lower in drought-treated plants (Xu et al., 2010). The results demonstrated that a 6% concentration of foliar spray had the most substantial impact on increasing number of leaves, followed by 3% and 0% concentrations. Specifically, the trend in increasing number of leaves was 6% > 3% > 0% foliar spray. This pattern was consistent across both 'nadir' and 'naqib' varieties under different water availability conditions (Akhtar et al., 2023), as shown in the bar graph (Fig. 7).

Chlorophyll a Content

Statistical data showed a highly significant interaction ($P < 0.01$) between various foliar spray concentrations and water stress treatments. Graphical data indicated that foliar spray had a noteworthy impact on chlorophyll a content. Chlorophyll a content was notably lower in drought-treated plants, but foliar spray improved the chlorophyll a content all Plants under stress as well as those not compared to the control (Tayyab et al., 2020). The results demonstrated that a 6% concentration of foliar spray had the most substantial impact on increasing chlorophyll a content, followed by 3% and 0% concentrations. Specifically, the trend in increasing chlorophyll a was 6% > 3% > 0% foliar spray. This pattern was consistent across both 'nadir' and 'naqib' varieties under different water availability conditions (Blunden et al., 1996), as shown in the bar graph (Fig. 8).

Chlorophyll b Content

Statistical data showed a momentous interaction ($P < 0.01$) between various foliar spray concentrations and water stress treatments. Graphical data indicated that foliar spray had a significant prestige on chlorophyll b content was notably lower in drought-treated plants, but foliar spray improved the chlorophyll b content all plants under stress as well as those not compared to the control (Wasaya et al., 2021). As a result, the results demonstrated that a 6% concentration of foliar spray had the most substantial impact on increasing chlorophyll b, followed by 3% and 0% concentrations. Specifically, the trend in increasing chlorophyll b was 6% > 3% > 0% foliar spray. This pattern was consistent across both 'nadir' and 'naqib' varieties under different water availability conditions (Zonouri et al., 2014), as shown in the bar graph (Fig. 9).

Carotenoid Content

Statistical data showed a highly significant interaction ($P < 0.01$) between various foliar spray concentrations and water stress treatments. Graphical data indicated that foliar spray had a significant control on carotenoid content. Carotenoid content was notably lower in drought-treated plants, but foliar spray improved the carotenoid content all plants under stress as well as those not compared to the control (Saheri et al., 2020). As a result, the results demonstrated that a 6% concentration of foliar spray had the most substantial impact on increasing carotenoid content, followed by 3% and 0% concentrations. Specifically, the trend in increasing carotenoid content was 6% > 3% > 0% foliar spray. This pattern was consistent across both 'nadir' and 'naqib' varieties under different water availability conditions (Ikram et al., 2025) as shown in the bar graph (Fig. 10).

Shoot Anthocyanin Content

Statistical data showed a momentous interaction ($P > 0.01$) between various foliar spray concentrations and water stress treatments. Graphical data indicated that foliar spray had a significant stimulus on shoot anthocyanin content. Shoot anthocyanin content was notably lower in drought-treated plants, but foliar spray improved the shoot anthocyanin content all Plants under stress as well as those not compared to the control (Zahedi et al., 2020). As a result, the results demonstrated that a 6% concentration of foliar spray had the most substantial impact on increasing shoot anthocyanin contents, followed by 3% and 0% concentrations. Specifically, the trend in increasing SAC was 6% > 3% > 0% foliar spray. This pattern was consistent across both 'nadir' and 'naqib' varieties under different water availability conditions (Pratap et al., 2004) as shown in the bar graph (Fig. 11).

Root Anthocyanin Content

Statistical data showed a non-significant interaction ($P > 0.01$) between various foliar spray concentrations and water stress treatments. Graphical data indicated that foliar spray had a significant impact on root anthocyanin content. Root anthocyanin content was notably lower in drought-treated plants, but foliar spray improved the root anthocyanin content all plants under stress as well as those not compared to the control (Feyissa et al., 2019). As a result, the results demonstrated that a 6% concentration of foliar spray had the most substantial impact on increasing RAC, followed by 3% and 0% concentrations. Specifically, the trend in increasing RAC was 6% > 3% > 0% foliar spray. This pattern was consistent across both 'nadir' and 'naqib' varieties under different water availability conditions (Pantoja-Benavides et al., 2021), as shown in the bar graph (Fig. 12).

Shoot Flavonoid Content

Statistical data showed a non-significant interaction ($P > 0.01$) between various foliar spray concentrations and water stress treatments. Graphical data indicated that foliar spray had a significant stimulus on shoot flavonoid content. Shoot flavonoid content was notably lower in drought-treated plants, but foliar spray improved the shoot flavonoid content all plants under stress as well as those not compared to the control (Ahmadi et al., 2020). As a result, the results demonstrated that a 6% concentration of foliar spray had the most substantial impact on increasing SFC, followed by 3% and 0% concentrations. Specifically, the trend in increasing SFC was 6% > 3% > 0% foliar spray. This pattern was consistent across both 'nadir' and 'naqib' varieties under different water availability conditions (Niu et al., 2021), as shown in the bar graph (Fig. 13).

Root Flavonoid Content

Statistical data showed a momentous interaction ($P > 0.01$) between various foliar spray concentrations and water stress treatments. Graphical data indicated that foliar spray had a significant influence on root flavonoid content. Root flavonoid content was notably lower in drought-treated plants, but foliar spray improved the root flavonoid content all plants under stress as well as those not compared to the control (Ahmed et al., 2021). As a result, the results demonstrated that a 6% concentration of foliar spray had the most substantial impact on increasing RFC, followed by 3% and 0% concentrations. Specifically, the trend in increasing RFC was 6% > 3% > 0% foliar spray. This pattern was consistent across both 'nadir' and 'naqib' varieties under different water availability conditions (Voogt et al., 2013), as shown in the bar graph (Fig. 14).

Shoot Soluble Sugar Content

Statistical data showed a non-significant interaction (P > 0.01) between various foliar spray concentrations and water stress treatments. Graphical data indicated that foliar spray had a significant impact on shoot soluble sugar content. Shoot soluble sugar content was notably lower in drought-treated plants, but foliar spray improved the shoot soluble sugar content plants under stress as well as those not compared to the control (Gao et al., 2022). As a result, the results demonstrated that a 6% concentration of foliar spray had the most substantial impact on increasing SSC of shoots, followed by 3% and 0% concentrations. Specifically, the trend in increasing SSC of shoots was 6% > 3% > 0% foliar spray. This pattern was consistent across both 'nadir' and 'naqib' varieties under different water availability conditions (Faizan & Hayat, 2019) as shown in the bar graph (Fig. 15).

Root soluble Sugar Content

Statistical data showed a highly significant interaction (P < 0.01) between various foliar spray concentrations and water stress treatments. Graphical data indicated that foliar spray had a significant stimulus on root soluble sugar content. Root soluble sugar content was notably lower in drought-treated plants, but foliar spray improved the root soluble sugar content Plants under stress as well as those not compared to the control (Yan et al., 2022). As a result, the results demonstrated that a 6% concentration of foliar spray had the most substantial impact on increasing SSC of root, followed by 3% and 0% concentrations. Specifically, the trend in increasing SSC of roots was 6% > 3% > 0% foliar spray. This pattern was consistent across both 'nadir' and 'naqib' varieties under different water availability conditions (Ghazijahani et al., 2014) as shown in the bar graph (Fig. 16).

Shoot Ascorbic Acid Content

Statistical data showed a highly significant interaction (P < 0.01) between various foliar spray concentrations and water stress treatments. Graphical data indicated that foliar spray had a significant stimulus on shoot ascorbic acid content. Shoot ascorbic acid content was notably lower in drought-treated plants, but foliar spray improved the shoot ascorbic acid content all plants under stress as well as those not compared to the control (Iftikhar et al., 2025). As a result, the results demonstrated that a 6% concentration of foliar spray had the most substantial impact on increasing AAC of shoots, followed by 3% and 0% concentrations. Specifically, the trend in increasing AAC of shoots was 6% > 3% > 0% foliar spray. This pattern was consistent across both 'nadir' and 'naqib' varieties under different water availability conditions (Aslam et al., 2016) as shown in the bar graph (Fig. 17).

Root Ascorbic Acid Content

Statistical data showed non-significant interaction (P > 0.01) between various foliar spray concentrations and water stress treatments. Graphical data indicated that foliar spray had a significant inspiration on root ascorbic acid content. Root ascorbic acid content was notably lower in drought-treated plants, but foliar spray improved the root ascorbic acid content Plants under stress as well as those not compared to the control (Huang et al., 2022). As a result, the results demonstrated that a 6% concentration of foliar spray had the most substantial impact on increasing AAC of roots, followed by 3% and 0% concentrations. Specifically, the trend in increasing AAC of roots was 6% > 3% > 0% foliar spray. This pattern was consistent across both 'nadir' and 'naqib' varieties under different water availability conditions (Roosta & Mohsenian, 2012), as shown in the bar graph (Fig. 18).

Shoot Hydrogen Peroxide Content

Statistical data showed non-significant interaction (P > 0.01) between various foliar spray concentrations and water stress treatments. Graphical data indicated that foliar spray had significant influence shoot hydrogen peroxide content. Shoot hydrogen peroxide content was notably lower in drought-treated plants, but foliar spray improved the shoot hydrogen peroxide content Plants under stress as well as those not compared to the control (Qi et al., 2025). As a result, the results demonstrated that a 6% concentration of foliar spray had the most substantial impact on increasing HPC of shoots, followed by 3% and 0% concentrations. Specifically, the trend in increasing HPC of shoots was 6% > 3% > 0% foliar spray. This pattern was consistent across both 'nadir' and 'naqib' varieties under different water availability conditions (Fang et al., 2019), as shown in the bar graph (Fig. 19).

Root Hydrogen Peroxide Content

Statistical data showed non-significant interaction (P > 0.01) between various foliar spray concentrations and water stress treatments. Graphical data indicated that foliar spray had a significant influence root hydrogen peroxide content. Root hydrogen peroxide content was notably lower in drought-treated plants, but foliar spray improved the root hydrogen peroxide content Plants under stress as well as those not compared to the control (Guler & Pehlivan, 2016). As a result, the results demonstrated that a 6% concentration of foliar spray had the most substantial impact on increasing HPC of roots, followed by 3% and 0% concentrations. Specifically, the trend in increasing HPC of roots was 6% > 3% > 0% foliar spray. This pattern was consistent across both 'nadir' and 'naqib' varieties under different water availability conditions (Akhtar, 2018), as shown in the bar graph (Fig. 20).

Ion Analysis

Shoot Calcium Content

Statistical data showed non-significant interaction (P > 0.01) between various foliar spray concentrations and water stress treatments. Graphical data indicated that foliar spray had a significant impact on shoot calcium content. Shoot calcium content was notably lower in drought-treated plants, but foliar spray improved the shoot calcium content all plants under stress as well as those not compared to the control (Akhtar, 2018). As a result, the results demonstrated that a 6% concentration of foliar spray had the most substantial impact on increasing CC of shoots, followed by 3% and 0% concentrations. Specifically, the trend in increasing CC of shoots was 6% > 3% > 0% foliar spray. This pattern was consistent across both 'nadir' and 'naqib' varieties under different water availability conditions (Khan, 2016), as shown in the bar graph (Fig. 21).

Root Calcium Content
Statistical data showed non-significant interaction (P > 0.01) between various foliar spray concentrations and water stress treatments. Graphical data indicated that foliar spray had significant influence root calcium content. Root calcium content was notably lower in drought-treated plants, but foliar spray improved the root calcium content Plants under stress as well as those not compared to the control (Y. Wang et al., 2023). As a result, the results demonstrated that a 6% concentration of foliar spray had the most substantial impact on increasing CC of roots, followed by 3% and 0% concentrations. Specifically, the trend in increasing CC of roots was 6% > 3% > 0% foliar spray. This pattern was consistent across both 'nadir' and 'naqib' varieties under different water availability conditions (MINIATURES, 2008) as shown in the bar graph (Fig. 22).

Shoot Potassium Content
Statistical data showed non-significant interaction (P > 0.01) between various foliar spray concentrations and water stress treatments. Graphical data indicated that foliar spray had a significant influence shoot potassium content. Shoot potassium content was notably lower in drought-treated plants, but foliar spray improved the shoot potassium content plants under stress as well as those not compared to the control (Farooq et al., 2009). As a result, the results demonstrated that a 6% concentration of foliar spray had the most substantial impact on increasing PC of shoot, followed by 3% and 0% concentrations. Specifically, the trend in increasing PC of shoot was 6% > 3% > 0% foliar spray. This pattern was consistent across both 'nadir' and 'naqib' varieties under different water availability conditions (Chapagain & Wiesman, 2004), as shown in the bar graph (Fig. 23).

Root Potassium Content
Statistical data showed non-significant interaction (P > 0.01) between various foliar spray concentrations and water stress treatments. Graphical data indicated that foliar spray had significant effect root potassium content. Root potassium content was notably lower in drought-treated plants, but foliar spray improved the root potassium content Plants under stress as well as those not compared to the control (Chapagain & Wiesman, 2004). As a result, the results demonstrated that a 6% concentration of foliar spray had the most substantial impact on increasing PC of root, followed by 3% and 0% concentrations. Specifically, the trend in increasing PC of root was 6% > 3% > 0% foliar spray. This pattern was consistent across both 'nadir' and 'naqib' varieties under different water availability conditions (Jameel et al., 2024), as shown in the bar graph (Fig. 24).

Shoot Sodium Content
Statistical data showed a non-significant interaction (P > 0.01) between various foliar spray concentrations and water stress treatments. Graphical data indicated that foliar spray had a significant inspiration on shoot sodium content. Shoot sodium content was notably lower in drought-treated plants, but foliar spray improved the shoot sodium content of plants under stress as well as those not compared to the control (Kaya & Shabala, 2023). As a result, the results demonstrated that a 6% concentration of foliar spray had the most substantial impact on increasing SC of shoot, followed by 3% and 0% concentrations. Specifically, the trend in increasing SC of shoot was 6% > 3% > 0% foliar spray. This pattern was consistent across both 'nadir' and 'naqib' varieties under different water availability conditions (Khan, 2016), as shown in the bar graph (Fig. 25).

Root Sodium Content
Statistical data showed a non-significant interaction (P > 0.01) between various foliar spray concentrations and water stress treatments. Graphical data indicated that foliar spray had a significant impact on root sodium content. Root sodium content was notably lower in drought-treated plants, but foliar spray improved the root sodium content of Plants under stress as well as those not compared to the control (Khan, 2016). As a result, the results demonstrated that a 6% concentration of foliar spray had the most substantial impact on increasing SC of root, followed by 3% and 0% concentrations. Specifically, the trend in increasing SC of rootss was 6% > 3% > 0% foliar spray. This pattern was consistent across both 'nadir' and 'naqib' varieties under different water availability conditions (Bailey, 1996), as shown in the bar graph (Fig. 26).

Figure 1
Effect of Moringa Leaf Extract on Shoot Fresh Weight Under Drought Stress

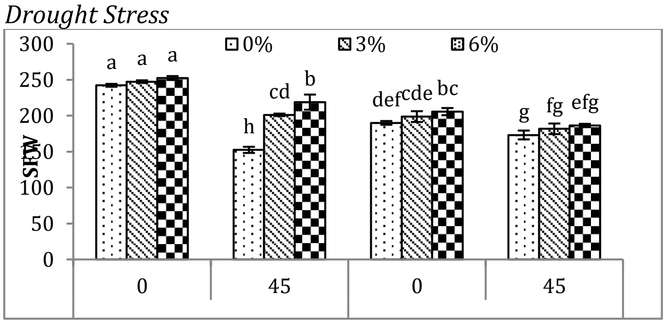


Figure 2
Effect of Moringa Leaf Extract on Root Fresh Weight Under Drought Stress

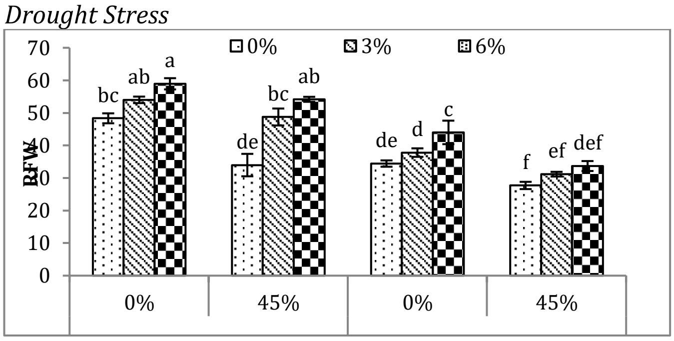


Figure 3
Effect of Moringa Leaf Extract on Shoot Dry Weight Under Drought Stress

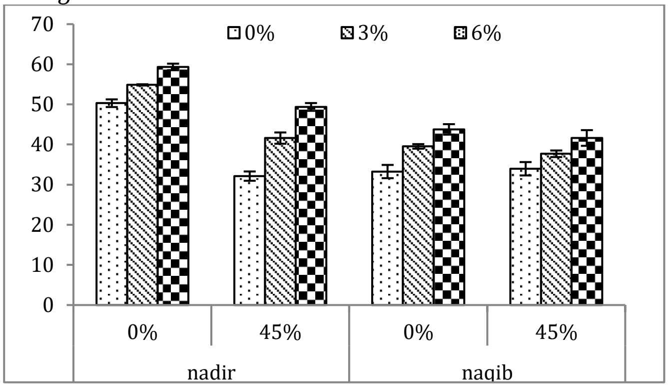


Figure 7
Effect of Moringa Leaf Extract on Number of Leavers Under Drought Stress

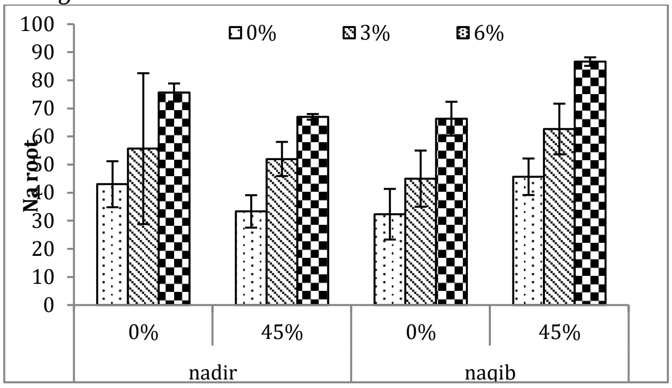


Figure 4
Effect of Moringa Leaf Extract on Root Dry Weight Under Drought Stress

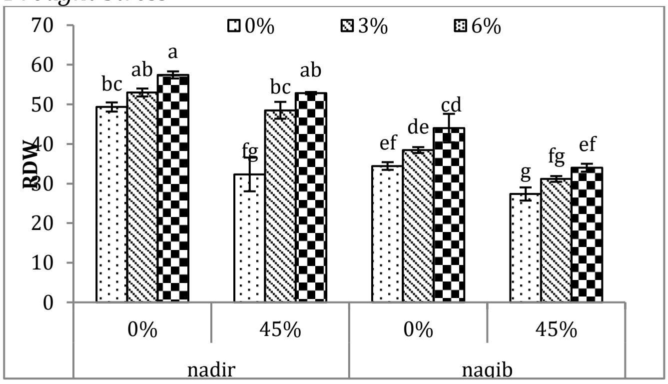


Figure 8
Effect of Moringa Leaf Extract on Chl A Content Under Drought Stress

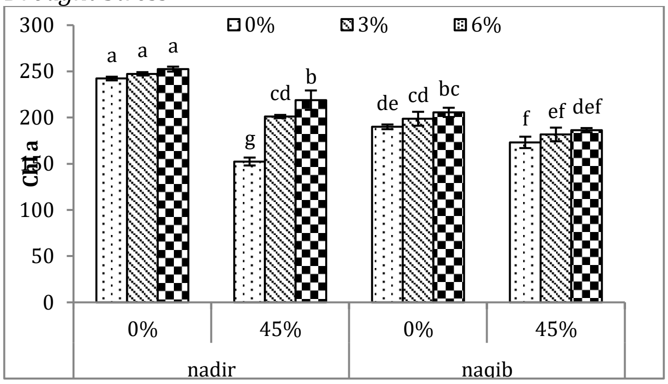


Figure 5
Effect of Moringa Leaf Extract on Shoot Length Under Drought Stress

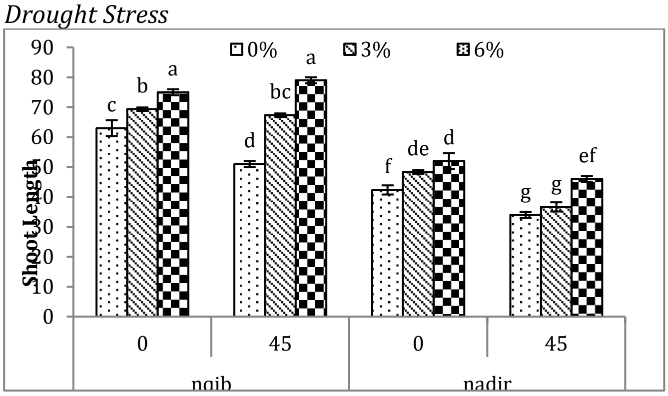


Figure 9
Effect of Moringa Leaf Extract on Chl B Content Under Drought Stress

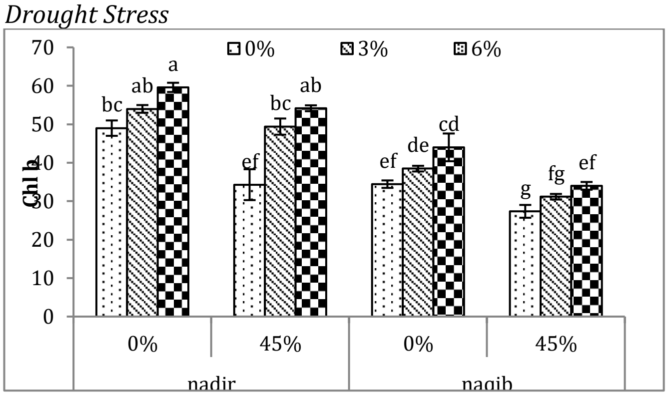


Figure 6
Effect of Moringa Leaf Extract on Root Length Under Drought Stress

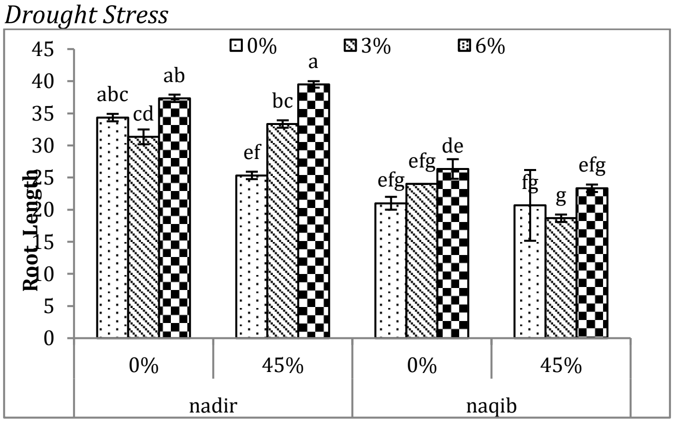


Figure 10
Effect of Moringa Leaf Extract on Carotenoid Content Under Drought Stress

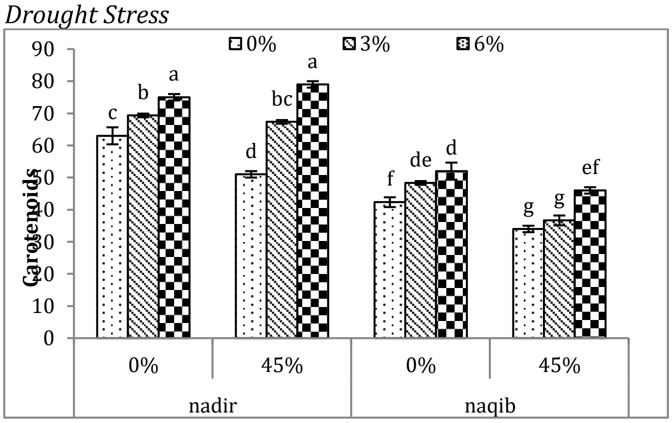


Figure 11

Effect of Moringa Leaf Extract on Root Anthocyanin Under Drought Stress

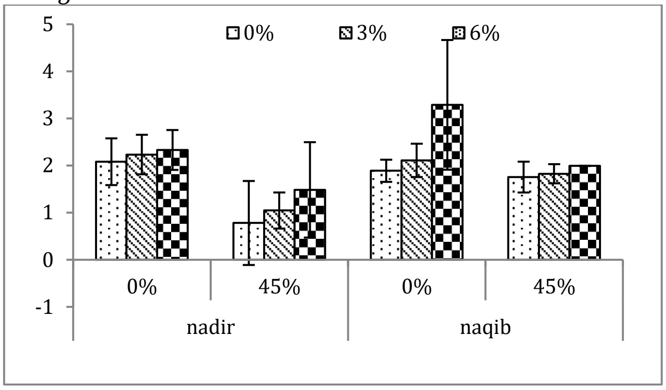


Figure 12

Effect of Moringa Leaf Extract on Shoot Flavonoids Under Drought Stress

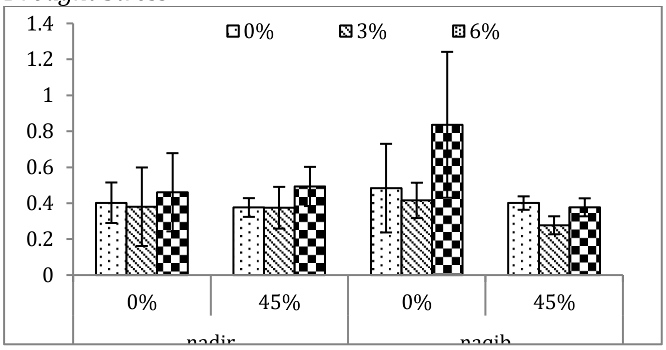


Figure 13

Effect of Moringa Leaf Extract on Root Flavonoids Under Drought Stress

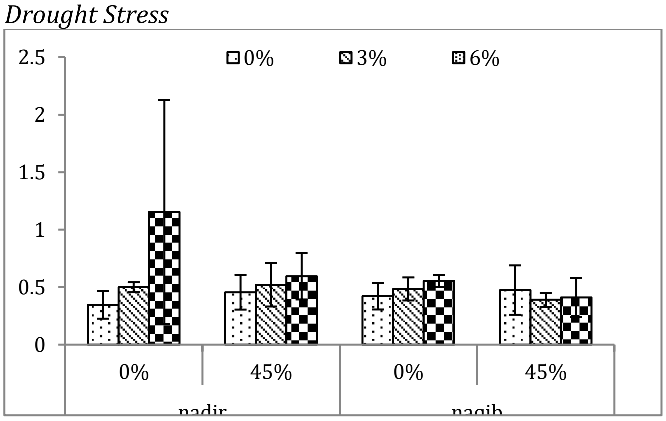


Figure 14

Effect Of Moringa Leaf Extract ONz Shoot Soluble Sugar Under Drought Stress

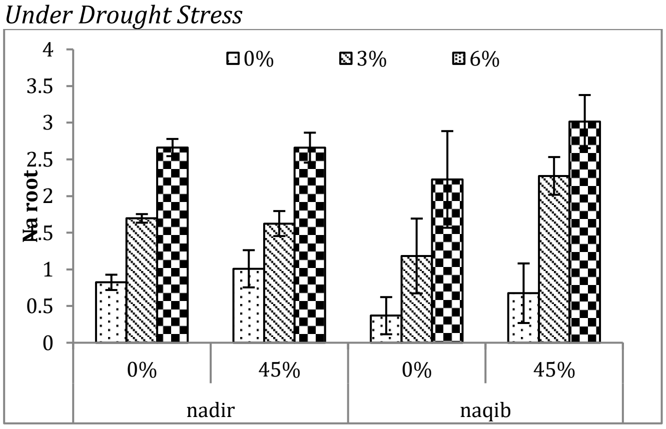


Figure 15

Effect of Moringa Leaf Extract on Root Soluble Sugar Under Drought Stress

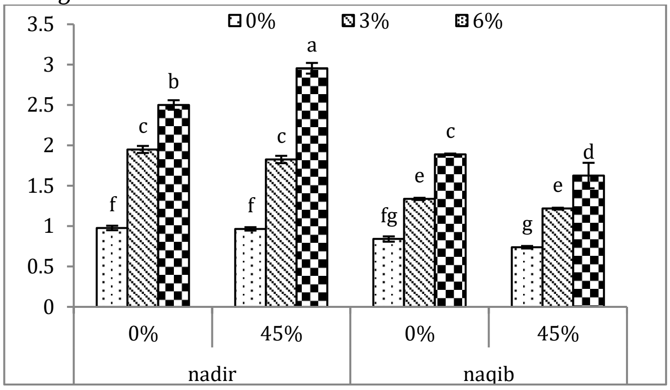


Figure 16

Effect of Moringa Leaf Extract on Shoot Ascorbic Acid Under Drought Stress

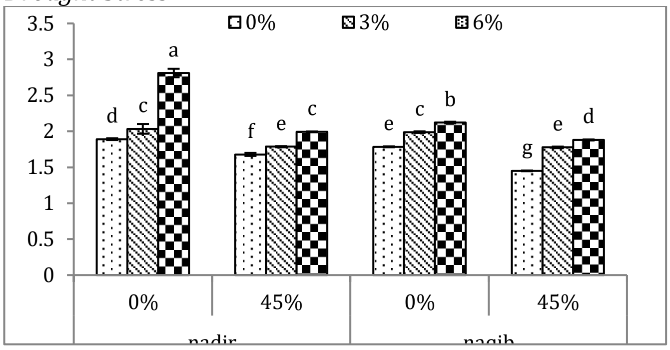


Figure 17

Effect of Moringa Leaf Extract on Root Ascorbic Acid Under Drought Stress

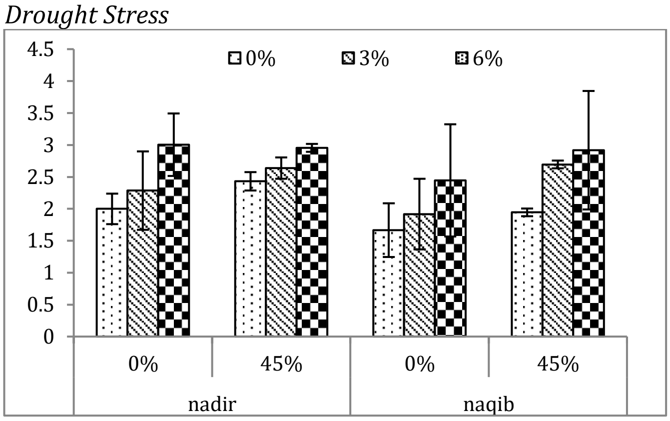


Figure 18

Effect of Moringa Leaf Extract on Shoot H2o2 Under Drought Stress

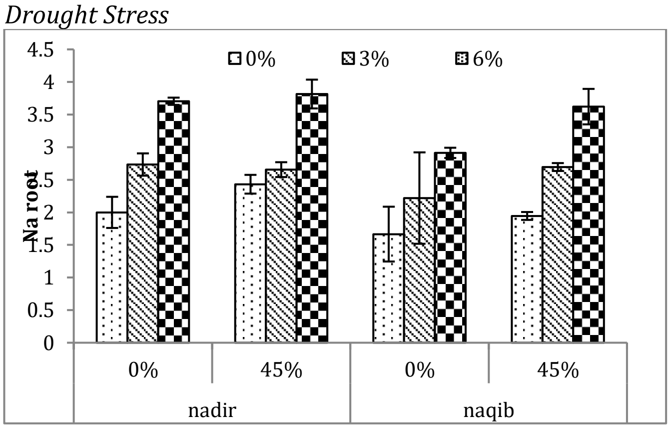


Figure 19

Effect of Moringa Leaf Extract on Root H2o2 Under Drought Stress

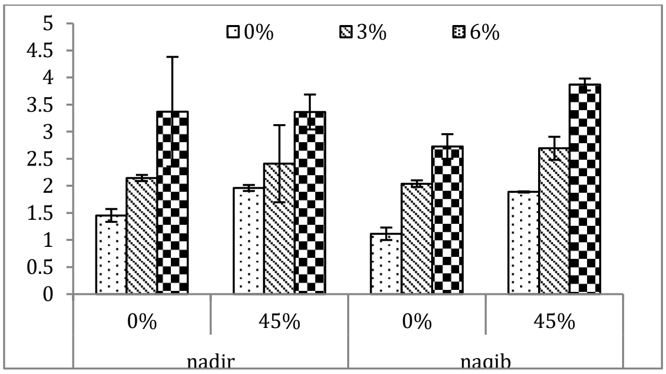


Figure 20

Effect of Moringa Leaf Extract on Shoot Calcium Content Under Drought Stress

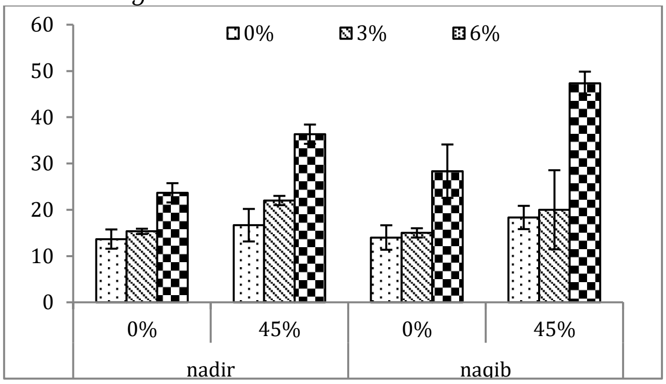


Figure 21

Effect of Moringa Leaf Extract on Root Calcium Content Under Drought Stress

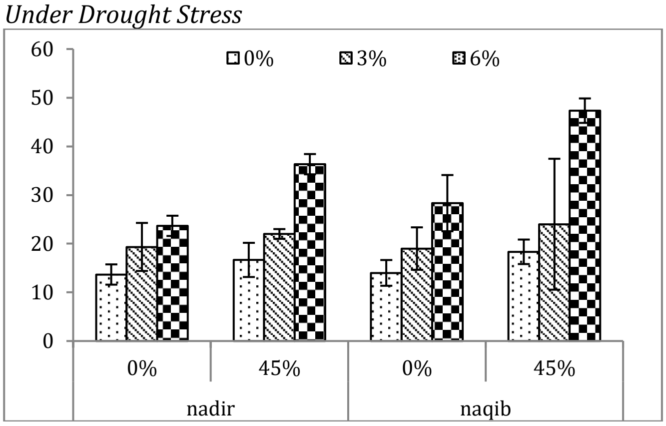


Figure 22

Effect of Moringa Leaf Extract on Shoot Potassium Content Under Drought Stress

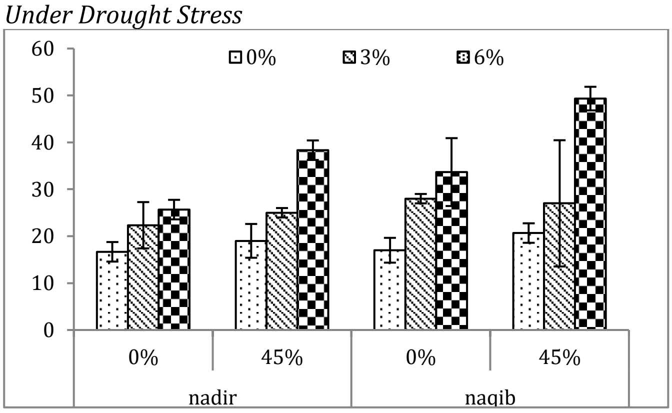


Figure 23

Effect of Moringa Leaf Extract on Root Potassium Content Under Drought Stress

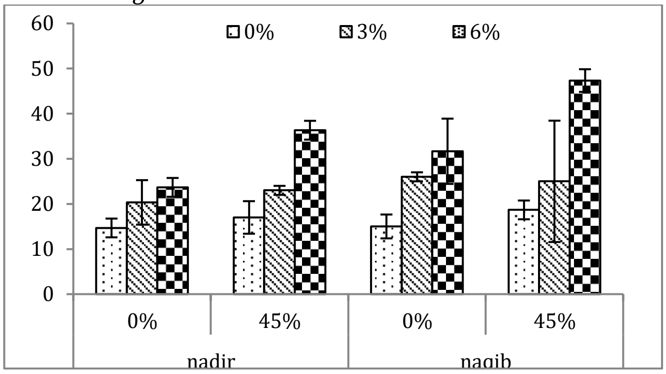


Figure 24

Effect of Moringa Leaf Extract on Shoot Sodium Content Under Drought Stress

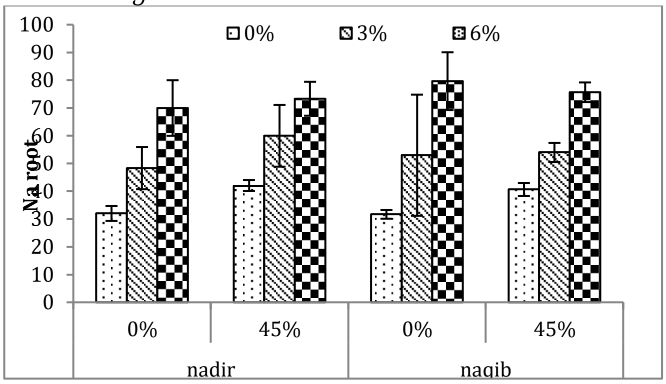
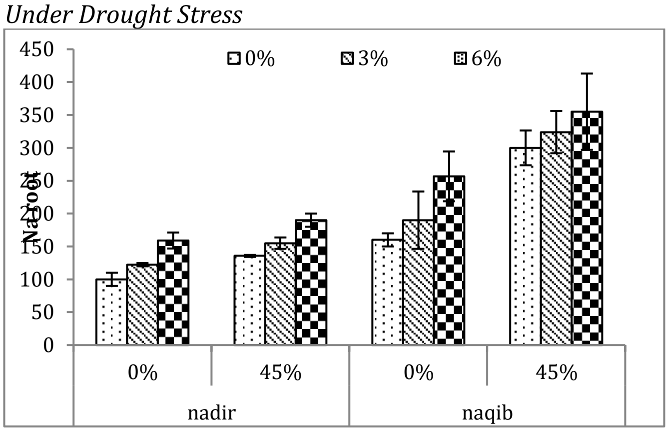


Figure 25

Effect of Moringa Leaf Extract on Root Sodium Content Under Drought Stress



The tomato, or Solanum lycopersicum, is a vegetable crop that is grown and consumed worldwide and is prized for both its nutritional worth and economic significance. Unfortunately, abiotic stresses drought in particular have a substantial adverse effect on tomato plants development, output, and fruit quality. According to (X. Wang et al., 2023), drought stress upsets the water balance, which lowers photosynthesis, nutrient uptake, and eventually plant productivity. Several agronomic approaches have been studied to mitigate the negative effects of drought stress, such as the use of biostimulants.

Rich in vitamins, minerals, hormones, and antioxidants, Moringa oleifera leaf extract (MLE) is one promising biostimulant (Yasmeen et al., 2013). According to reports, when exposed to abiotic stress, moringa leaf extract improves plant development, increases stress tolerance, and increases yield in a number of crops (Rady et al., 2021).

Drought stress effects a number of physiological and biochemical restrictions in tomato plants. Moringa oleifera, sometimes known as the drumstick tree, is gaining popularity due to its rich nutritional profile and medicinal properties. Moringa leaves are rich in vitamins, minerals, amino acids, and phytohormones, including cytokinin, which is known to stimulate plant growth and development. Foliar application of Moringa leaf extract (MLE) has been demonstrated to increase plant growth, stress tolerance, and yield in a range of crops under abiotic stress conditions. This study was lead at the historic botanic garden to evaluate effects of foliar application of Moringa leaf extract on tomato growing performance under drought stress. Two tomato varieties, Nadir and Naqib, were used in the experiment. The experimental setup involved three different concentrations of MLE (0%, 3%, and 6%) and two levels of field capacity (45% and 100%).

The main goal was to find out how MLE affects tomatoes that are experiencing a water scarcity in terms of growth performance, physiological reactions, and stress tolerance. There were three replications and a fully randomized sequence used in the experiment. Plants were evenly sowed in pots. Following thirty days of flowering, the plants were subjected to a water deficit and then an extract from moringa leaves. Following a 30-day growth period in which there was a water discrepancy, the crop was harvested and various growth metrics were assessed. Numerous biochemical and ion studies were conducted using the relevant procedures.

The present research established that under drought stress, plant growth is harshly reduced as exemplified by vegetative parameters such as plant size, root and shoot length, fresh and dry weight of root and shoot. In disparity, moringa leaf extract application enhanced all plant growth metrics when compared to control group. Seeing the interaction effects, it is evident that moringa leaf extract markedly amended every aspect of tomato growth. The optimum enhances in 600% moringa leaf extract dosage. These results are aligned with those that were obtained by (Khadr et al., 2021).

In the existing trial, water stress results in a substantial decrease in shoot diameter, the leaf number and roots, whereas an increase is shown in these metrics when moringa leaf extract is sprayed particularly at 600% dosage. These conclusions are in line with those reported by (Bakry et al., 2012).

According to recent studies, when the leaf area of plants was deficient in water, they saw a significant reduction in growth, whereas the plants treated with moringa leaf extract exhibited improved leaf area. Similar findings were obtained by preliminary research studies on numerous crops (Farooq & Koul, 2020). Current research revealed that drought treatment diminished tomato development and growth development by inhibiting the activities of growth enzymes and cell division procedure. In contrast, ascorbic acid promoted these metrics. These results are aligned with those that were found by (Ghorbanli et al., 2010).

Present studies described that chlorophyll contents drastically lowered during drought conditions. While externally applied moringa leaf stimulated the chlorophyll components chlorophyll a, chlorophyll b, and carotenoid contents (Malik & Ashraf, 2012) also established similar findings. Anthocyanin contents declined during water stress whereas foliar spray of moringa leaf increased these contents in current study. Similar findings were determined by early study carried out by (Alayafi, 2020). However, the mechanism is not much studied.

The current research explained that there is a decline in flavonoids and soluble sugar contents. I noticed that optimal doses of moringa leaf extract had optimistic influence on flavonoids, and soluble sugar contents. These findings are in agreement with the ones that were published by (Amira & Qados, 2014). In this research, the enhancement in the ratios of H_2O_2 noted in drought-treated plants.

In this experiment, I tracked how the extract from moringa leaves affected the proportion of non-enzymatic antioxidants in the leaf during water deficit. A recent study found that ionic concentrations were lower in crops under water stress. Whereas a rise in Na^+, K^+, and Ca^{+2} ions occurs when moringa leaf dosages are increased. Other researchers observed similar findings (Arora et al., 2008).

CONCLUSION

The foliar application of Moringa leaf extract significantly improved the growth performance of tomato plants under drought stress conditions. Treated plants exhibited enhanced morphological traits such as increased plant height, leaf number, and biomass compared to untreated controls. The bioactive compounds present in Moringa, including cytokinin, antioxidants, and essential nutrients, played a crucial role in mitigating the adverse effects of water deficiency by enhancing physiological and biochemical responses. These findings suggest that Moringa leaf extract is an effective, natural, and sustainable biostimulant that can be integrated into drought management strategies to improve tomato productivity under limited water availability.

Ethics approval and consent to participate: NA

Consent for publication: Not applicable

Availability of data and materials: All data is available in the manuscript

Acknowledgment: The authors are thankful to the Department of Botany, University of Agriculture Faisalabad, Pakistan.

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