# PHYSIOLOGICAL AND MORPHOLOGICAL ADAPTATIONS OF MAIZE (ZEA MAYS L.) UNDER VARYING ENVIRONMENTAL CONDITIONS: IMPLICATIONS FOR GROWTH AND YIELD

*Original Article*

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## ABSTRACT

**Background:** Maize (Zea mays L.), a globally important cereal crop, faces significant yield constraints due to increasing environmental stressors such as drought, heat, salinity, and soil nutrient deficiencies. Climate change and declining soil fertility continue to jeopardize food security in many maize-growing regions. Understanding the physiological and morphological responses of maize to these abiotic stress factors is crucial for developing climate-resilient cultivars and optimizing agronomic practices for sustainable production.

**Objective:** This study aimed to evaluate the physio-morphological responses of maize under controlled and field-imposed abiotic stress conditions to inform breeding and management strategies for improved tolerance and yield stability.

**Methods:** Field and greenhouse experiments were conducted using a drought- and heat-tolerant maize hybrid. Stress conditions—drought, heat, salinity, and nutrient deficiency—were simulated using water regulation, temperature-controlled chambers, NaCl applications, and nutrient variation, respectively. Physiological parameters (photosynthetic rate, stomatal conductance, osmolyte content, hormone levels) and morphological traits (plant height, leaf area index, root length) were assessed using standardized instrumentation including LI-COR 6400XT, SPAD meter, and root scanning software. Yield and reproductive traits were analyzed post-harvest.

**Results:** Drought reduced plant height from 180 cm to 140 cm and photosynthetic rate from 28 to 18 µmol $CO_2$ m$^{-2}$ s$^{-1}$, while increasing root length to 50 cm and proline content to 9.8 µmol/g FW. Heat stress lowered chlorophyll content to 38 SPAD units and pollen viability to 70%. Salinity induced a rise in ABA to 70 ng/g FW and root length to 45 cm. Nutrient deficiency decreased chlorophyll to 32 SPAD and grain yield to 7000 kg/ha. Grain yield under drought fell by 27.8% compared to control.

**Conclusion:** Abiotic stress significantly impairs maize growth and yield through physiological disruptions, despite morphological compensations. Integrating stress-responsive traits in breeding programs and precision agronomy is essential for improving maize resilience and productivity under changing climates.

**Keywords:** Chlorophyll, drought tolerance, heat stress, maize, photosynthesis, salinity, yield.

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# INTRODUCTION

Maize (Zea mays L.) stands as one of the world's most essential cereal crops, serving as a primary food source, livestock feed, and raw material for various industrial products. Its global cultivation is attributed to its genetic diversity and phenotypic plasticity, which allow it to thrive across a wide range of environments, from temperate to tropical regions. However, the sustainability of maize production is increasingly threatened by dynamic climate variables such as temperature fluctuations, water scarcity, soil nutrient depletion, and salinity stress (1). These abiotic factors are becoming more unpredictable and severe due to climate change, thereby posing a growing risk to maize productivity and global food security (2). In this context, it becomes imperative to understand the physiological and morphological adaptations that enable maize to survive and maintain yield stability under such environmental pressures. Existing literature emphasizes that maize possesses a range of physiological mechanisms to counteract abiotic stress, including stomatal regulation, osmotic adjustment, hormonal signaling, and efficient photosynthesis (3). As a C4 plant, maize exhibits superior water-use efficiency and carbon assimilation compared to C3 plants such as wheat and rice, enabling it to maintain higher productivity under heat and drought conditions (4). The accumulation of compatible solutes like proline, glycine betaine, and soluble sugars also supports osmotic balance and cell integrity during stress events (5). Hormonal mediators such as abscisic acid (ABA), cytokinins, and auxins further modulate stress responses by regulating stomatal conductance, root growth, and reproductive development (6). These physiological adaptations form a crucial line of defense against drought, salinity, and extreme temperatures.

Complementing these internal mechanisms are morphological traits that help the maize plant withstand harsh conditions. A robust root system with greater depth and lateral spread allows access to moisture and nutrients from deeper soil layers, significantly enhancing drought resilience (7). Leaf structural modifications, such as increased cuticle thickness, reduced stomatal density, and upright leaf orientation, contribute to efficient water conservation and light interception under stressful environments (8). Moreover, adaptations in reproductive architecture, including altered flowering time and increased silk and pollen viability, support successful pollination and kernel development even under temperature stress (9). These structural traits, in combination with physiological responses, form a complex adaptive network that ensures survival and productivity. Temperature stress, particularly during critical reproductive stages, has been shown to accelerate phenological development, shorten grain filling periods, and reduce overall yield (10). High temperatures can compromise pollen viability, hinder silk receptivity, and impair kernel set, while cold temperatures inhibit germination and metabolic functions (11). Heat stress also triggers the production of heat shock proteins (HSPs) and induces lipid modifications in cell membranes to maintain structural integrity and enzyme function (12). Similarly, salinity imposes osmotic and ionic stress that interferes with nutrient uptake and cellular metabolism, often resulting in reduced growth and productivity. To mitigate these effects, maize engages in selective ion compartmentalization, particularly retaining potassium ions while restricting sodium accumulation in the cytoplasm (13). However, maize remains comparatively less tolerant to salinity than some other cereals, necessitating targeted interventions to enhance tolerance. Soil nutrient availability significantly affects maize's capacity to manage abiotic stress. Deficiencies in nitrogen, phosphorus, and potassium disrupt physiological functions such as chlorophyll synthesis, root development, and water regulation, ultimately reducing biomass and grain yield (14). Adaptive strategies such as enhancing nutrient transporter gene expression, developing symbiotic relationships with mycorrhizal fungi, and releasing root exudates to mobilize nutrients in the rhizosphere have been documented as crucial for improving nutrient use efficiency (15). To further strengthen resilience, agronomic practices like conservation tillage, mulching, precision irrigation, and biofertilizer application have demonstrated positive impacts on maize yield under stress conditions (16). The integration of advanced genetic tools has revolutionized maize breeding for stress tolerance. Techniques such as marker-assisted selection (MAS), Agrobacterium-mediated transformation, and CRISPR-based genome editing have accelerated the development of climate-resilient maize varieties by incorporating allelic variants that confer tolerance to drought, heat, and nutrient deficiencies (17). Despite these advancements, the increasing complexity and frequency of environmental stressors demand a more comprehensive understanding of maize's adaptive traits. Future research must prioritize the identification and deployment of multi-stress tolerance genes, alongside optimizing field-level management practices, to ensure sustainable maize production in the face of escalating climatic uncertainty. Therefore, this study aims to critically examine the physiological and morphological adaptations of maize to environmental stressors such as drought, heat, salinity, and nutrient limitations. By understanding these complex adaptive mechanisms, the research seeks to inform breeding programs and agronomic practices for the development of climate-resilient maize varieties, thereby contributing to global food security in an era of environmental unpredictability.

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## METHODS

The present study was designed to evaluate the physiological and morphological responses of maize (Zea mays L.) to a range of environmental stresses, including drought, high and low temperatures, salinity, and nutrient deficiency. Field and greenhouse experiments were carried out to simulate both controlled and natural stress conditions. The greenhouse trials were conducted under regulated climatic conditions, while the field experiments were performed at an agricultural research station characterized by semi-arid climatic conditions, including variable rainfall, temperature extremes, and sandy-loam soil to mimic real-world environmental variability. The maize genotype used was a locally cultivated, drought- and heat-tolerant hybrid commonly grown in semi-arid regions, selected for its adaptability and relevance to stress-prone agro-ecological zones. A randomized complete block design (RCBD) with three replicates per treatment was employed to ensure experimental precision and minimize variability. Treatments included a well-watered and optimally nourished control group alongside multiple stress treatments: drought (mild, moderate, and severe), temperature fluctuations (heat and cold), saline soil conditions (with increasing concentrations of NaCl), and varying levels of NPK nutrient deficiency. Each treatment was applied in separate and systematically arranged plots or greenhouse sections to avoid cross-contamination and enable accurate data interpretation.

Drought stress was induced by regulating irrigation levels to one-third, two-thirds, and complete withholding relative to the full irrigation baseline, representing mild, moderate, and severe drought, respectively. Soil moisture content in the greenhouse was monitored using digital soil moisture sensors, while rainout shelters in the field blocked precipitation, ensuring controlled drought exposure. Stress levels were further categorized based on leaf water content, with 70% indicating mild, 50% moderate, and below 30% representing severe stress conditions. Temperature stress was applied through temperature-controlled chambers in the greenhouse, with daytime heat stress maintained at 38–42 °C and nighttime cold stress at 10–15 °C. Additionally, field trials were aligned with seasonal extremes to capture natural temperature variability. Canopy and ambient temperatures were continuously monitored using thermocouples and infrared thermometers. Salinity stress was imposed by irrigating plants with sodium chloride (NaCl) solutions at concentrations of 50, 100, and 150 mM to simulate mild, moderate, and severe salinity, respectively. Soil electrical conductivity was routinely measured using EC meters to ensure the accuracy and consistency of salt levels. Leaching was conducted periodically to prevent salt accumulation that could induce osmotic shock beyond the intended thresholds. Nutrient deficiency treatments were created by modifying soil nutrient content, particularly reducing nitrogen, phosphorus, and potassium in controlled proportions. Control plots received full nutrient application, while treated plots were administered half-strength and three-quarter-strength nutrient solutions. Key physiological metrics including plant phytomass, chlorophyll content, and root development were used as indicators of nutrient limitation.

Plant growth and morphological assessments were performed at vegetative, reproductive, and grain-filling stages. Plant height, leaf area index (LAI), and aboveground biomass were recorded biweekly using digital calipers, a portable leaf area meter, and a biomass oven. Root system architecture was analyzed by carefully uprooting plants, scanning roots using a root imaging system, and calculating root length, surface area, and root-to-shoot ratio using image analysis software. Leaf morphology, including stomatal density, cuticle thickness, and epicuticular wax deposition, was examined using both light microscopy and scanning electron microscopy. Canopy traits such as leaf angle and light interception were assessed using a ceptometer to determine canopy efficiency under stress. Photosynthetic performance and gas exchange parameters were measured using a portable photosynthesis system (LI-COR 6400XT). Net photosynthetic rate (Pn), stomatal conductance (gs), transpiration rate (E), and intracellular $CO_2$ concentration (Ci) were recorded. Chlorophyll fluorescence parameters, particularly the quantum yield of Photosystem II (PSII), were also assessed to evaluate photochemical efficiency under stress. Chlorophyll content was quantified using a SPAD chlorophyll meter, which served as a non-destructive proxy for nutrient status and salinity-induced chlorophyll degradation.

Osmotic adjustment was studied by quantifying biochemical markers such as proline, glycine betaine, and soluble sugars in leaf tissues. These compounds were extracted and quantified using the ninhydrin assay and the anthrone method, respectively. Leaf samples were collected from each treatment group and processed in a certified plant physiology laboratory. Hormonal responses to stress were analyzed by measuring abscisic acid (ABA), cytokinins, and ethylene levels in both leaf and root tissues using enzyme-linked immunosorbent assay (ELISA) and high-performance liquid chromatography (HPLC). ABA was a particular focus due to its role in stomatal closure and root development during water stress. Reproductive performance was assessed through phenological observations, including flowering time, anthesis-silking interval (ASI), and pollen viability. Pollen viability was tested via acetocarmine staining and in vitro germination assays. The development of reproductive structures, including silks and kernels, was recorded to evaluate stress-induced fertility changes. At physiological maturity, grain yield components were measured, including kernels per cob, 1000-kernel weight, and harvest index. Grain quality assessments, including starch and protein content, were conducted using Near-Infrared Reflectance Spectroscopy (NIRS). Yield losses under each stress condition were quantified relative to the control group.

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All data were statistically analyzed using SPSS software (v26.0) and R programming (v4.2.1). A one-way analysis of variance (ANOVA) was employed to determine the significance of treatment effects. Where significant differences were found, Tukey's HSD test was used for pairwise comparison. Pearson's correlation analysis was conducted to explore the relationships between physiological traits, morphological attributes, and yield performance. Additionally, principal component analysis (PCA) was performed to identify key traits associated with stress tolerance. Predictive modeling, including regression analysis, random forest, and support vector regression, was used to identify the major determinants of maize adaptability under stress. Ethical approval for this study was obtained from the Institutional Research and Ethics Committee of the hosting agricultural research institution under protocol number IRB/AGRES/MAIZE2024/032. All experimental procedures complied with institutional and national guidelines for plant research. Although human participants were not involved, standard research integrity and biosafety protocols were maintained throughout the experimental period.

## RESULTS

Maize plants exhibited notable physiological and morphological changes in response to environmental stressors, including drought, heat, salinity, and nutrient deficiency. Across all stress conditions, plant growth was negatively impacted, with the most significant reductions observed under drought and nutrient-deficient treatments. Plant height declined from 180 cm in the control group to 140 cm under drought stress, while the leaf area index (LAI) decreased from 3.5 to 2.7. Leaf number and stem diameter also showed measurable reductions. Conversely, root length increased under stress, rising from 35 cm in the control to 50 cm under drought and 45 cm under salinity, indicating a compensatory adaptation to enhance water and nutrient absorption. Photosynthetic parameters demonstrated a consistent downward trend under stress. The net photosynthetic rate decreased from 28 µmol $CO_2$ m$^{-2}$ s$^{-1}$ in the control to 18 µmol $CO_2$ m$^{-2}$ s$^{-1}$ under drought stress. Stomatal conductance dropped from 0.45 to 0.22 mol $H_2O$ m$^{-2}$ s$^{-1}$, while transpiration rate declined from 5.8 to 3.2 mmol $H_2O$ m$^{-2}$ s$^{-1}$. These reductions were accompanied by decreased intercellular $CO_2$ concentration and altered water use efficiency. A similar trend was observed in pigment content, with total chlorophyll (SPAD) falling from 45 in the control to 30 under drought and carotenoid content reducing from 0.42 mg/g FW to 0.28 mg/g FW, impairing photosynthetic efficiency.

Hormonal responses revealed a marked elevation in abscisic acid (ABA) under stress, increasing from 20 ng/g FW in control to 80 ng/g FW under drought. Ethylene production also doubled, rising from 3.5 to 7.2 nL/g FW/hr. Conversely, cytokinins and gibberellins decreased, suggesting a stress-induced hormonal imbalance influencing growth and reproductive processes. Morphological root adaptations included an increase in the number of lateral roots, from 2 in control to 11 under drought, reflecting an adaptive mechanism to enhance water acquisition. Osmotic regulation was evidenced by elevated levels of proline and glycine betaine, particularly under drought and salinity, with proline content rising from 3.2 to 9.8 µmol/g FW. Malondialdehyde (MDA), a marker of oxidative damage, increased from 2.0 to 6.1 µmol/g FW, highlighting enhanced lipid peroxidation under stress. Concurrently, antioxidant enzyme activity, such as superoxide dismutase (SOD), increased to mitigate oxidative stress.

Reproductive performance declined significantly in stressed plants. Pollen viability fell from 92% in the control to 50% under drought, and kernel number per cob dropped from 520 to 350. The anthesis-silking interval extended from 2.1 to 6.5 days, indicating delayed flowering synchronization. Kernel abortion rates increased to 28.5%, while 1000-kernel weight decreased from 320 g in the control to 240 g under drought. Grain yield was notably affected, with control plants yielding 9000 kg/ha, compared to only 6500 kg/ha under drought stress—a 27.78% reduction. Salinity and heat stress also reduced yield to 6800 kg/ha and 7200 kg/ha, respectively. Starch content declined across all stress treatments, dropping from 72% to 65%, while protein content increased slightly, possibly due to nitrogen remobilization under limited photosynthetic activity.

A statistically significant positive correlation was observed between photosynthetic rate and final grain yield. Regression analysis confirmed that reductions in photosynthetic efficiency directly influenced grain yield outcomes. This pattern underlines the critical importance of maintaining photosynthetic activity for securing yield under stress conditions. The observed reduction in leaf area index (from 3.5 in the control to 2.7 under nutrient deficiency and 2.8 under drought) may imply limited leaf expansion and increased investment in protective structures like thicker cuticles and wax layers to minimize transpirational loss. These protective features are commonly upregulated under drought and salinity stress to enhance water-use efficiency. Additionally, the increase in root dry weight under drought (from 12.5 g in control to 18.3 g) and salinity (16.2 g) further supports reallocation of assimilates away from shoot expansion and toward structures aiding water acquisition and conservation. Although specific values for wax deposition and cuticle thickness were not recorded, the elevated water-use efficiency under stress (rising to 5.6 under drought and 5.7 under salinity, compared to 4.8 in control) aligns with reduced stomatal conductance and likely structural reinforcement of the epidermal layers. Canopy light

interception, as reflected indirectly through LAI and chlorophyll content, showed a decline across stress treatments, which could reduce photosynthetic area but also serve to minimize heat load, especially under drought and heat conditions.

**Table 1: Growth Parameters Under Different Stress Conditions**

| Stress Condition | Plant Height (cm) | Stem Diameter (mm) | Leaf Number per Plant | Leaf Area Index (LAI) | Root Length (cm) | Root Dry Weight (g) |
|---|---|---|---|---|---|---|
| Control | 180 | 25 | 16 | 3.5 | 35 | 12.5 |
| Drought | 140 | 18 | 12 | 2.8 | 50 | 18.3 |
| Heat Stress | 160 | 20 | 14 | 3.1 | 40 | 14.8 |
| Salinity | 150 | 19 | 13 | 2.9 | 45 | 16.2 |
| Nutrient Deficiency | 145 | 17 | 12 | 2.7 | 42 | 15.0 |

**Table 2: Combined Stress Response Parameters in Maize under Environmental Constraints**

| | Control | Drought | Heat Stress | Salinity | Nutrient Deficiency |
|---|---|---|---|---|---|
| Photosynthetic and Gas Exchange Parameters | | | | | |
| Photosynthetic Rate ($\mu$mol $CO_2$ $m^{-2}$ $s^{-1}$) | 28 | 18 | 22 | 20 | 21 |
| Stomatal Conductance (mol $H_2O$ $m^{-2}$ $s^{-1}$) | 0.45 | 0.22 | 0.3 | 0.28 | 0.25 |
| Transpiration Rate (mmol $H_2O$ $m^{-2}$ $s^{-1}$) | 5.8 | 3.2 | 4.1 | 3.5 | 3.8 |
| Intercellular $CO_2$ Concentration (ppm) | 280 | 200 | 230 | 215 | 220 |
| Water Use Efficiency (WUE) | 4.8 | 5.6 | 5.3 | 5.7 | 5.4 |
| Chlorophyll and Pigment Content | | | | | |
| Chlorophyll a (mg/g FW) | 2.5 | 1.6 | 2 | 1.8 | 1.7 |
| Chlorophyll b (mg/g FW) | 0.9 | 0.5 | 0.7 | 0.6 | 0.5 |
| Total Chlorophyll (SPAD) | 45 | 30 | 38 | 35 | 32 |
| Carotenoid Content (mg/g FW) | 0.42 | 0.28 | 0.35 | 0.3 | 0.32 |
| Hormonal Response Under Stress | | | | | |
| Abscisic Acid (ABA, ng/g FW) | 20 | 80 | 60 | 70 | 65 |
| Cytokinins (ng/g FW) | 45 | 25 | 30 | 28 | 26 |
| Gibberellins (GA, ng/g FW) | 55 | 30 | 40 | 35 | 38 |
| Ethylene Production (nL/g FW/hr) | 3.5 | 7.2 | 5.8 | 6.5 | 6 |
| Osmotic Adjustment and Antioxidant Activity | | | | | |
| Proline Content ($\mu$mol/g FW)" cell | 3.2 | 9.8 | 5.6 | 7.3 | 6.1 |
| Glycine Betaine ($\mu$mol/g FW) | 2.1 | 6.4 | 4.2 | 5.1 | 4.5 |
| Soluble Sugars (mg/g FW) | 22.5 | 35.2 | 28.6 | 30.1 | 27.8 |
| Malondialdehyde (MDA, $\mu$mol/g FW) | 2 | 6.1 | 4.8 | 5.2 | 4.5 |

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| | Control | Drought | Heat Stress | Salinity | Nutrient Deficiency |
|---|---|---|---|---|---|
| Superoxide Dismutase (SOD, U/g FW) | 95 | 140 | 120 | 130 | 125 |
| Reproductive Performance | | | | | |
| Anthesis-Silking Interval (days) | 2.1 | 6.5 | 4.8 | 5.3 | 5 |
| Pollen Viability (%) | 92 | 50 | 70 | 65 | 72 |
| Kernel Number per Cob | 520 | 350 | 420 | 380 | 400 |
| Kernel Abortion Rate (%) | 8 | 28.5 | 18 | 22 | 19.5 |
| 1000-Kernel Weight (g) | 320 | 240 | 270 | 250 | 260 |

**Table 3: Grain Yield and Quality Parameters**

| Stress Condition | Grain Yield (kg/ha) | Harvest Index (%) | Starch Content (%) | Protein Content (%) | Oil Content (%) |
|---|---|---|---|---|---|
| Control | 9000 | 48 | 72 | 9.5 | 4.2 |
| Drought | 6500 | 42 | 65 | 11.2 | 4.8 |
| Heat Stress | 7200 | 45 | 68 | 10.0 | 4.5 |
| Salinity | 6800 | 43 | 66 | 10.5 | 4.6 |
| Nutrient Deficiency | 7000 | 44 | 67 | 10.2 | 4.4 |

**Table 4: Statistical Analysis of Key Traits**

| Trait | Control (Mean ± SD) | Drought (Mean ± SD) | Heat Stress (Mean ± SD) | Salinity (Mean ± SD) | Nutrient Deficiency (Mean ± SD) |
|---|---|---|---|---|---|
| Plant Height | 180 ± 5 | 140 ± 7 | 160 ± 6 | 150 ± 5 | 145 ± 6 |
| Root Length | 35 ± 2 | 50 ± 3 | 40 ± 2.5 | 45 ± 2.8 | 42 ± 2.6 |
| Photosynthetic Rate | 28 ± 1.5 | 18 ± 1.3 | 22 ± 1.4 | 20 ± 1.5 | 21 ± 1.4 |
| Chlorophyll Content | 45 ± 1.8 | 30 ± 1.5 | 38 ± 1.6 | 35 ± 1.7 | 32 ± 1.5 |
| Grain Yield | 9000 ± 320 | 6500 ± 280 | 7200 ± 300 | 6800 ± 290 | 7000 ± 310 |

## Grain Yield and Harvest Index Across Stress Conditions



## Photosynthetic Rate and Chlorophyll Content Across Stress Conditions



## Circular Representation of Kernel Number per Cob



## Heatmap of Photosynthetic Response Under Stress

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# DISCUSSION

This study provided a comprehensive evaluation of the physiological and morphological responses of maize (Zea mays L.) under the influence of four major abiotic stress factors: drought, heat, salinity, and nutrient deficiency. The results reflected how these environmental constraints significantly influenced growth parameters, photosynthetic efficiency, osmotic regulation, and yield-related traits, thus validating the hypothesis that maize adopts a series of stress-specific adaptation mechanisms to sustain productivity under adverse conditions. Drought stress emerged as the most limiting factor for maize development. The observed decline in plant height, leaf area index, and photosynthetic rate under water-deficit conditions was consistent with established findings that associate water scarcity with reduced cell expansion and impaired leaf development, leading to diminished photosynthetic activity and biomass production (3,6). Enhanced root elongation in drought-stressed plants further supported the hypothesis of compensatory root development for deeper water foraging, a well-recognized survival strategy in water-limited environments (5,10). However, such morphological adjustments did not fully compensate for the physiological restrictions caused by stomatal closure, which conserved water at the expense of $CO_2$ uptake and carbon assimilation. This trade-off between water conservation and photosynthetic capacity represents a critical bottleneck in drought tolerance.

Heat stress similarly impacted maize physiology, primarily by disrupting chlorophyll integrity and enzyme function, which compromised photosynthetic performance. The decline in chlorophyll content and pigment degradation under elevated temperatures aligned with prior studies linking thermal stress to photoinhibition and damage to the photosynthetic apparatus (13). Reproductive impairments were evident through reductions in pollen viability, extended anthesis-silking intervals, and reduced kernel number, indicating that heat stress compromised both gametophyte development and fertilization processes. These findings confirmed that maize is particularly vulnerable during the reproductive phase, reinforcing the importance of identifying and integrating thermotolerance traits in breeding programs (15). Salinity stress influenced both above- and below-ground plant traits, with reductions in chlorophyll content and plant stature suggesting ionic toxicity and osmotic inhibition of growth (17,18). The accumulation of compatible osmolytes such as proline and glycine betaine under saline conditions reflected an intrinsic stress response to maintain osmotic balance and cellular stability. Increased root length under salinity stress also mirrored a common plant adaptation to explore soil for diluted ionic zones and maintain water uptake. Despite these adaptive traits, the yield penalties associated with salinity stress highlighted the limited effectiveness of these responses under severe or prolonged salt exposure.

Nutrient deficiency, particularly of key macronutrients such as nitrogen, phosphorus, and potassium, also resulted in significant growth suppression. Reductions in chlorophyll content and photosynthetic rate under nutrient-limited conditions were consistent with the biochemical roles of these nutrients in pigment synthesis and energy metabolism. Yield attributes such as kernel number and weight declined, emphasizing the indispensable role of adequate nutrition in sustaining physiological processes and reproductive success. Although plants exhibited some degree of resilience by adjusting osmolyte content and root morphology, nutrient scarcity posed a substantial constraint to carbon assimilation and biomass allocation (19). One of the most significant observations from this study was the strong positive correlation between photosynthetic efficiency and grain yield across all stress conditions. This reinforces the centrality of maintaining photosynthetic integrity under stress for securing yield. Breeding efforts, therefore, should prioritize traits that enhance water-use efficiency, chlorophyll retention, and carbon fixation under environmental constraints (20).

A major strength of this study was the integration of multiple stress treatments within a controlled and field-based design, providing a holistic picture of maize adaptability. The use of quantitative physiological and morphological indicators added robustness to the findings. However, certain limitations must be acknowledged. Despite the mention of structural adaptations such as leaf wax deposition, cuticle thickness, and light interception, these traits were not quantitatively reported. Including such data would have enriched the analysis of physical protective mechanisms. Moreover, the study relied on a single maize genotype, which restricts the generalizability of findings across diverse genetic backgrounds. Future investigations should include genotype comparisons and molecular profiling to identify underlying genetic determinants of stress tolerance. Additionally, the experimental duration may not fully capture the cumulative effects of chronic stress exposure, particularly under fluctuating field conditions. Extended trials across multiple seasons would provide deeper insights into long-term adaptive performance. Integration of transcriptomic and proteomic analyses would also enhance understanding of regulatory networks governing stress responses.

In conclusion, this study successfully demonstrated the diverse and interconnected physiological and morphological responses of maize under abiotic stress. The findings underscore the need for targeted breeding strategies that integrate both structural and functional

resilience traits. The complexity of stress responses highlights the necessity for multidisciplinary approaches combining genetics, agronomy, and environmental modeling to develop climate-resilient maize cultivars suitable for future agricultural landscapes.

## CONCLUSION

This study concluded that maize exhibits a range of physiological and morphological adaptations in response to drought, heat, salinity, and nutrient deficiency, including altered root architecture, osmolyte accumulation, hormonal adjustments, and changes in photosynthetic efficiency. While these responses help sustain the plant under environmental stress, they often come with trade-offs in terms of reduced growth and yield. The findings emphasize the importance of integrating these adaptive traits into maize breeding programs and agronomic practices to enhance resilience and productivity in the face of climate variability. Strengthening these stress-responsive mechanisms holds significant promise for improving crop performance and ensuring food security under increasingly challenging environmental conditions.

**Author Contributions**

| Author | Contribution |
|---|---|
| Shoukat Ali Soomro* | Substantial Contribution to study design, analysis, acquisition of Data |
| | Manuscript Writing |
| | Has given Final Approval of the version to be published |
| Muhammad Akhtar | Substantial Contribution to study design, acquisition and interpretation of Data |
| | Critical Review and Manuscript Writing |
| | Has given Final Approval of the version to be published |
| Qurban Ali Magsi | Substantial Contribution to acquisition and interpretation of Data |
| | Has given Final Approval of the version to be published |
| Gul Hassan Shaikh | Contributed to Data Collection and Analysis |
| | Has given Final Approval of the version to be published |
| Maria Khan Pathan | Contributed to Data Collection and Analysis |
| | Has given Final Approval of the version to be published |
| Ghulam Abid Dharejo | Substantial Contribution to study design and Data Analysis |
| | Has given Final Approval of the version to be published |
| Ihsan Ullah | Contributed to study concept and Data collection |
| | Has given Final Approval of the version to be published |

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