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ADVANCES IN PLANT SCIENCE: GROWTH, DEVELOPMENT, AND SUSTAINABILITY

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Abstract

This experimental study investigates the physiological and molecular responses of maize (Zea mays L.) under drought stress conditions using controlled greenhouse experiments. A total of 90 maize plants were exposed to three irrigation regimes representing 100%, 60%, and 40% field capacity over a 60-day growth period to evaluate drought-induced effects on plant performance. Key growth and physiological parameters including plant height, biomass accumulation, chlorophyll content, and stomatal conductance were analyzed alongside the expression of drought-responsive genes DREB2A and NAC1. The results revealed significant reductions in plant height (−32%) and biomass accumulation (−41%) under severe drought stress conditions ($p < 0.001$), indicating the substantial negative impact of water deficiency on maize growth and productivity. However, drought-tolerant genotypes maintained significantly higher chlorophyll content (SPAD value: 42.3 ± 2.1) compared with susceptible varieties (31.7 ± 1.8), demonstrating enhanced physiological adaptability under stress conditions. Gene expression analysis further revealed a 3.5-fold upregulation of DREB2A in tolerant plants, highlighting the important role of molecular defense mechanisms in drought adaptation. The findings emphasize the integrated contribution of physiological and genetic responses in improving crop resilience under climate stress. This study provides valuable insights for the development of climate-resilient maize cultivars and supports the integration of plant science innovations into sustainable agricultural systems to mitigate the adverse impacts of climate change.

INTRODUCTION

Agriculture is one of the most important sectors supporting global food security, economic development, and human survival. However, climate change has emerged as a major threat to agricultural sustainability, particularly through the increasing frequency and severity of drought stress. Drought is considered one of the most destructive abiotic stresses affecting crop productivity worldwide because it limits water availability required for plant growth and physiological functioning. Maize (Zea mays L.) is among the most widely cultivated cereal crops and serves as a staple food source for millions of people across the world. Due to its high water requirement during vegetative and reproductive growth stages, maize is highly vulnerable to drought stress, which can significantly reduce plant growth, biomass accumulation, photosynthetic activity, and grain yield. Consequently, improving drought tolerance in maize has become a major focus of modern agricultural and plant science research. Plants exposed to drought conditions undergo a variety of physiological, biochemical, and molecular changes to survive under water-limited environments. Physiological responses such as reduced stomatal conductance, chlorophyll degradation, and impaired biomass accumulation are common indicators of drought stress. At the molecular level, drought-responsive genes including DREB2A and NAC1 play essential roles in regulating stress adaptation pathways. These genes activate protective mechanisms such as osmotic adjustment, antioxidant defense, and stress signaling processes that help plants tolerate adverse environmental conditions. Understanding the interaction between physiological responses and molecular regulation is therefore essential for developing climate-resilient crop varieties.\n\nRecent advances in plant biotechnology, molecular genetics, and sustainable agriculture have provided new opportunities to enhance drought tolerance in crops. Researchers are increasingly focusing on integrating physiological measurements with gene expression analysis to better understand plant adaptation mechanisms. Such integrated studies contribute to the development of drought-tolerant cultivars capable of maintaining productivity under changing climatic conditions. The present study was therefore designed to investigate the physiological and molecular responses of maize plants subjected to different drought stress conditions under controlled greenhouse experiments. The findings of this research aim to provide valuable scientific insight into drought adaptation mechanisms and support sustainable agricultural strategies for future food security.

Several previous studies have investigated the impact of drought stress on plant growth and physiological performance in cereal crops, particularly maize. Researchers have consistently reported that water deficit conditions significantly reduce plant height, biomass production, leaf area, and grain yield due to impaired photosynthetic efficiency and nutrient transport. According to earlier studies, drought stress reduces cell turgor pressure and limits cell expansion, resulting in suppressed vegetative growth. Reduced biomass accumulation under drought conditions has also been associated with decreased carbon assimilation caused by stomatal closure and chlorophyll degradation. These physiological limitations ultimately reduce crop productivity and agricultural profitability in drought-prone regions.Chlorophyll stability and stomatal conductance are widely recognized as important physiological indicators of drought tolerance in plants. Previous investigations demonstrated that drought-tolerant genotypes maintain higher chlorophyll content compared with susceptible varieties under stress conditions. Higher SPAD values are associated with improved photosynthetic performance, greater carbon fixation, and enhanced plant survival. Similarly, studies on stomatal behavior revealed that drought stress causes partial or complete stomatal closure to minimize water loss through transpiration. Although this response conserves water, prolonged stomatal closure also restricts carbon dioxide uptake, negatively affecting photosynthesis and plant growth.\n\nAt the molecular level, considerable research has focused on drought-responsive genes and their regulatory roles in stress adaptation. Genes such as DREB2A, NAC1, WRKY, and MYB transcription factors have been identified as major regulators of drought tolerance pathways in plants. Previous gene expression studies reported that drought stress induces significant upregulation of DREB2A, which activates downstream stress-responsive genes involved in osmoprotection, antioxidant activity, and cellular defense. NAC family genes have also been linked with improved root architecture, stress signaling, and maintenance of cellular integrity during water scarcity. Advances in quantitative real-time PCR technology have enabled researchers to accurately evaluate gene expression responses under environmental stress conditions. In recent years, sustainable agriculture and climate resilience have become central themes in plant science research. Scientists have emphasized the need for integrating physiological, molecular, and agronomic approaches to improve drought tolerance in crops. Modern breeding programs increasingly utilize molecular markers and stress-responsive genes to develop climate-smart cultivars capable of maintaining productivity under adverse environmental conditions. Despite significant progress, drought stress remains a major challenge affecting maize production globally, highlighting the importance of continued research in this field. Although numerous studies have examined the effects of drought stress on maize physiology and productivity, several important research gaps still exist. Most previous studies focused either on physiological responses or molecular mechanisms independently, with limited integration of both approaches within a single experimental framework. As a result, there remains insufficient understanding of the relationship between physiological traits such as chlorophyll content, stomatal conductance, biomass accumulation, and the expression of drought-responsive genes under varying irrigation conditions. Furthermore, many earlier investigations primarily emphasized field-based agronomic observations without conducting detailed molecular analysis of stress-responsive genes. While genes such as DREB2A and NAC1 have been individually studied, limited research has evaluated their expression patterns simultaneously with physiological measurements under controlled greenhouse environments. The lack of integrated studies combining physiological and molecular parameters restricts the development of comprehensive drought adaptation models in maize plants. Another major gap involves the comparison between drought-tolerant and susceptible maize genotypes. Several previous studies evaluated only single genotypes or focused on yield performance without analyzing the underlying physiological and genetic mechanisms responsible for drought resilience. Consequently, there is limited information regarding how tolerant genotypes maintain chlorophyll stability, stomatal regulation, and enhanced gene activation under severe water deficit conditions. In addition, increasing climate variability and water scarcity require updated research focusing on sustainable agricultural strategies for crop improvement. Existing studies often lack practical implications for climate-resilient agriculture and fail to integrate physiological and molecular findings into sustainable crop management frameworks. Therefore, the present study addresses these limitations by combining growth analysis, physiological measurements, and gene expression profiling in maize under controlled drought stress conditions. The study aims to provide a comprehensive understanding of drought adaptation mechanisms and contribute valuable scientific evidence for the development of drought-tolerant maize cultivars suitable for sustainable agricultural production under climate change conditions

Experimental Design and Plant Material

The present experimental study was conducted under controlled greenhouse conditions to investigate the physiological and molecular responses of maize (Zea mays L.) under drought stress. A total of ninety healthy maize plants were selected for the experiment and distributed equally among three irrigation treatments representing different field capacities. The experiment was arranged using a completely randomized design (CRD) to minimize environmental variation and improve the reliability of the results. Three irrigation regimes were established, including 100% field capacity as the control treatment, 60% field capacity representing moderate drought stress, and 40% field capacity representing severe drought stress. Each treatment consisted of three biological replicates to ensure statistical accuracy and reproducibility of the data. Uniform seeds of drought-tolerant and susceptible maize genotypes were sterilized before sowing to prevent fungal contamination and ensure healthy germination. Plants were grown in plastic pots filled with a standardized soil mixture composed of loam soil, sand, and organic compost in equal proportions to maintain proper aeration and nutrient availability. Throughout the growth period, greenhouse temperature was maintained between 25–30°C with relative humidity ranging from 60–70%. Natural photoperiod conditions were supplemented with artificial lighting to maintain consistent light intensity for all experimental units. Irrigation treatments were initiated after seedling establishment and continued for sixty days. Soil moisture levels were monitored regularly using a digital moisture meter to maintain accurate field capacity conditions. All agronomic practices, including fertilization and pest management, were uniformly applied to avoid external interference. This experimental setup provided a controlled environment for evaluating the impact of water deficit stress on maize growth, physiology, and gene expression responses under sustainable agricultural research conditions.

Measurement of Growth and Physiological Parameters

Growth and physiological parameters were carefully measured throughout the experimental period to evaluate the impact of drought stress on maize development. Plant height was recorded at regular intervals using a calibrated measuring scale from the soil surface to the tip of the tallest leaf. Biomass accumulation was determined at the end of the experiment by harvesting plants, separating shoots and roots, and drying them in a hot air oven at 70°C until constant weight was achieved. Chlorophyll content was measured using a SPAD chlorophyll meter, which provided rapid and non-destructive estimation of leaf greenness and photosynthetic pigment concentration. Multiple leaves from each treatment were analyzed to obtain representative values for physiological assessment. Stomatal conductance was measured using a portable porometer during morning hours to minimize environmental fluctuations affecting transpiration rates. Measurements were taken from fully expanded leaves under stable greenhouse conditions to ensure consistency. Soil moisture content was monitored continuously to verify the maintenance of assigned irrigation treatments throughout the study period. In addition to physiological analysis, visual symptoms of drought stress such as leaf rolling, wilting, and chlorosis were also observed and recorded. Data collection was performed using standardized protocols to reduce experimental error and improve data accuracy. All observations were repeated in triplicate to ensure reliability and reproducibility of the findings. The collected growth and physiological data were used to assess drought tolerance mechanisms and identify differences between tolerant and susceptible maize genotypes. These measurements provided essential information regarding plant adaptation to water-limited conditions and contributed to understanding the relationship between drought stress and crop productivity. The integration of physiological indicators allowed comprehensive evaluation of maize performance under varying irrigation regimes and supported the development of sustainable agricultural strategies for drought-prone environments.

Molecular and Gene Expression Analysis

Molecular analysis was performed to investigate the expression patterns of drought-responsive genes in maize plants exposed to water stress conditions. Fresh leaf samples were collected from both tolerant and susceptible genotypes during the peak stress period and immediately preserved in liquid nitrogen to prevent RNA degradation. Total RNA was extracted using a commercial plant RNA extraction kit following the manufacturer's protocol. The quality and concentration of RNA were assessed using spectrophotometry and agarose gel electrophoresis to ensure integrity and purity before downstream analysis.

Complementary DNA (cDNA) synthesis was carried out using reverse transcriptase enzymes and standardized reaction mixtures. Quantitative real-time polymerase chain reaction (qRT-PCR) was performed to analyze the expression levels of drought-responsive genes, specifically DREB2A and NAC1, which are widely associated with stress adaptation and drought tolerance in plants. Gene-specific primers were designed and validated prior to amplification. The housekeeping gene actin was used as an internal control to normalize gene expression levels and minimize experimental variation. Relative gene expression was calculated using the $2-\Delta\Delta CT$ method to determine fold changes in response to drought stress. All reactions were performed in triplicate to ensure statistical reliability and reproducibility of the results. Amplification conditions, including annealing temperature and cycle number, were optimized to achieve accurate and efficient amplification. The molecular data obtained from gene expression analysis were correlated with physiological responses such as chlorophyll retention and biomass accumulation to better understand drought adaptation mechanisms. This integrated molecular approach provided valuable insight into the regulatory pathways activated under water deficit conditions and highlighted the importance of genetic factors in improving drought resilience. The findings also supported the potential application of molecular breeding and genetic engineering technologies for developing climate-resilient maize cultivars suitable for sustainable agriculture.

Statistical Analysis and Data Interpretation

All experimental data obtained from growth, physiological, and molecular analyses were statistically evaluated to determine the significance of drought stress effects on maize plants. Data collected from different irrigation treatments were organized using spreadsheet software and analyzed using statistical software packages. Mean values and standard deviations were calculated for all measured parameters, including plant height, biomass, chlorophyll content, stomatal conductance, and gene expression levels. One-way analysis of variance (ANOVA) was performed to identify statistically significant differences among treatment groups. When significant variation was detected, post hoc comparison tests were conducted to compare individual treatment means and identify the most affected parameters. A significance level of $p < 0.05$ was used to determine statistical reliability, while highly significant differences were reported at $p < 0.01$ and $p < 0.001$ levels. Graphical representations such as bar charts and line graphs were generated to visually illustrate treatment effects and trends observed during the experimental period. Correlation analysis was also conducted to examine relationships between physiological traits and gene expression responses under drought stress conditions. The statistical analysis confirmed that drought stress significantly affected maize growth, physiological performance, and molecular activity. Data interpretation focused on identifying adaptive mechanisms that contributed to drought tolerance and improved survival under limited water availability. The integration of statistical and graphical analysis enhanced the clarity and reliability of the findings, allowing accurate comparison between tolerant and susceptible genotypes. Furthermore, statistical validation strengthened the scientific credibility of the study and supported the conclusions regarding drought-induced physiological and molecular changes in maize plants. This analytical approach provided a comprehensive understanding of plant responses to environmental stress and contributed valuable information for future agricultural research and crop improvement programs focused on sustainable and climate-resilient farming systems.

Results and Discussion

The results presented in Table 1 demonstrate the substantial influence of drought stress on maize plant height under varying irrigation regimes. Plants grown under full irrigation conditions (100% field capacity) achieved the maximum average height of 152 cm, indicating optimal growth when sufficient water availability supports normal physiological and metabolic processes. Under moderate drought stress at 60% field capacity, plant height decreased to 124 cm, representing an 18% reduction compared with the control treatment. Severe drought stress at 40% field capacity resulted in a further decline in height to 103 cm, corresponding to a 32% reduction. This reduction indicates that limited water availability directly restricts cellular expansion, photosynthetic activity, and nutrient transport, all of which are essential for stem elongation and vegetative development. The progressive decline in plant height under drought conditions reflects the sensitivity of maize growth to soil moisture deficits. Water stress reduces turgor pressure within plant cells, thereby limiting cell division and elongation. In addition, drought-induced stomatal closure reduces carbon dioxide uptake and photosynthetic efficiency, leading to lower carbohydrate production necessary for biomass accumulation and structural growth. The results also suggest that maize plants prioritize survival over vegetative expansion under severe stress conditions. These findings are highly significant for agricultural sustainability because plant height is closely associated with crop vigor and productivity. Reduced plant height often correlates with lower leaf area, decreased light interception, and ultimately reduced grain yield. Therefore, maintaining adequate irrigation or developing drought-tolerant maize cultivars is essential for sustaining agricultural production under changing climatic conditions. The observed reductions highlight the urgent need for advanced irrigation management and genetic improvement programs aimed at enhancing drought resistance in maize cultivation.

Table 1: Plant Height Under Different Irrigation Regimes

Irrigation	Plant Height (cm)	Reduction (%)
100% FC	152	0
60% FC	124	18
40% FC	103	32

Table 2 illustrates the effect of drought stress on biomass accumulation in maize plants grown under different irrigation treatments. Biomass production was highest under well-watered conditions, with plants at 100% field capacity producing 210 g of biomass. Under moderate drought stress (60% field capacity), biomass decreased to 165 g, representing a 21% reduction. Severe drought stress at 40% field capacity caused a substantial decrease to 124 g, corresponding to a 41% reduction compared with the control. These results clearly indicate that water availability strongly influences dry matter accumulation and overall plant productivity. The reduction in biomass under drought conditions can be attributed to several physiological limitations. Drought stress restricts photosynthetic efficiency because stomatal closure reduces carbon dioxide uptake, thereby limiting carbohydrate synthesis. Lower carbohydrate production results in reduced energy availability for growth and metabolic activities. Additionally, drought stress affects nutrient absorption and translocation within plant tissues, leading to impaired protein synthesis and cellular development. Severe water deficit conditions may also increase oxidative stress, causing damage to cellular membranes and chloroplast structures. Biomass accumulation is considered one of the most reliable indicators of plant health and agricultural productivity. The significant reduction observed under severe drought demonstrates the vulnerability of maize crops to climate-induced water scarcity. Reduced biomass negatively impacts forage quality, grain production, and economic yield, posing serious challenges for food security in drought-prone regions. The findings emphasize the importance of adopting drought management strategies such as efficient irrigation systems, mulching, soil moisture conservation techniques, and the development of drought-resistant genotypes. Furthermore, the results support the integration of molecular breeding approaches aimed at improving biomass retention under stress conditions. Overall, the data confirm that drought stress severely limits maize productivity and highlight the necessity of sustainable agricultural practices to maintain crop performance under changing environmental conditions.

Table 2: Biomass Accumulation in Maize Plants

Irrigation	Biomass (g)	Reduction (%)
100% FC	210	0
60% FC	165	21
40% FC	124	41

Table 3 presents the chlorophyll content of drought-tolerant and susceptible maize genotypes measured using SPAD values. The tolerant genotype exhibited a significantly higher chlorophyll content of 42.3 ± 2.1 compared with the susceptible genotype, which recorded a lower SPAD value of 31.7 ± 1.8. These results indicate that drought-tolerant maize varieties possess a greater ability to maintain chlorophyll stability and photosynthetic activity under stress conditions. Chlorophyll is a critical pigment responsible for capturing light energy during photosynthesis. Under drought stress, chlorophyll degradation commonly occurs due to oxidative damage, reduced nutrient uptake, and disruption of chloroplast structures. The lower chlorophyll content observed in susceptible plants suggests that drought stress severely affected their photosynthetic machinery, leading to reduced energy production and limited plant growth. In contrast, tolerant genotypes maintained higher chlorophyll levels, indicating stronger protective mechanisms against oxidative stress and enhanced physiological adaptation. The preservation of chlorophyll content is directly associated with improved photosynthetic efficiency, carbon assimilation, and energy production. Higher SPAD values in tolerant plants suggest that these genotypes can sustain metabolic activity and growth even under limited water availability. This adaptive advantage contributes to better drought resilience, increased biomass retention, and improved survival under adverse environmental conditions. From an agricultural perspective, chlorophyll stability is an important trait for selecting drought-resistant cultivars. Breeding programs focusing on genotypes with enhanced chlorophyll retention can improve crop productivity in water-limited environments. Furthermore, SPAD measurements provide a rapid and non-destructive method for evaluating plant stress responses and screening drought-tolerant varieties. Overall, the findings demonstrate that chlorophyll content serves as an effective physiological indicator of drought tolerance in maize. The superior performance of tolerant genotypes highlights the importance of physiological adaptation mechanisms in maintaining crop productivity under climate stress conditions.

Table 3: Chlorophyll Content (SPAD Values)

Genotype	SPAD Value	Standard Deviation
Tolerant	42.3	2.1
Susceptible	31.7	1.8

The data presented in Table 4 reveal the effect of drought stress on stomatal conductance in maize plants under different irrigation regimes. Under full irrigation conditions (100% field capacity), stomatal conductance reached 310 mmol m−2 s−1, indicating active gas exchange and efficient photosynthetic performance. Under moderate drought stress (60% field capacity), conductance declined to 240 mmol m−2 s−1, while severe drought stress (40% field capacity) further reduced conductance to 170 mmol m−2 s−1. This progressive decline reflects the plant's physiological response to water deficit conditions. Stomata are microscopic pores located on leaf surfaces that regulate gas exchange and transpiration. Under drought stress, plants close their stomata to minimize water loss through transpiration. Although this response helps conserve water, it simultaneously limits carbon dioxide uptake required for photosynthesis. Reduced stomatal conductance therefore leads to lower photosynthetic rates, decreased carbohydrate synthesis, and reduced plant growth. The results indicate that severe drought stress significantly disrupts physiological functioning in maize plants. Reduced stomatal conductance may also increase leaf temperature and oxidative stress due to limited evaporative cooling. Furthermore, prolonged stomatal closure can impair nutrient transport and metabolic activity, contributing to reduced biomass accumulation and yield losses. These findings are important for understanding drought adaptation mechanisms in crops. Genotypes capable of maintaining moderate stomatal activity under water deficit conditions may achieve a balance between water conservation and photosynthetic efficiency. Such traits are highly desirable for developing drought-resilient maize varieties. From a practical perspective, monitoring stomatal conductance can provide valuable insights into plant water status and irrigation requirements. The observed reductions highlight the importance of efficient irrigation scheduling and drought management strategies in sustainable agriculture. Overall, the table confirms that drought stress strongly affects stomatal behavior, ultimately influencing photosynthesis, growth, and crop productivity.

Table 4: Stomatal Conductance Analysis

Irrigation	Conductance (mmol m-2 s-1)
100% FC	310
60% FC	240
40% FC	170

Table 5 presents the expression patterns of drought-responsive genes DREB2A and NAC1 in maize plants subjected to drought stress. The results demonstrate a 3.5-fold upregulation of DREB2A and a 2.8-fold increase in NAC1 expression under stress conditions. These findings indicate that drought stress activates molecular defense mechanisms that help plants adapt to water-limited environments. DREB2A is a well-known transcription factor associated with drought tolerance. Its activation regulates the expression of stress-responsive genes involved in osmotic adjustment, antioxidant defense, and cellular protection. The strong upregulation observed in this study suggests that DREB2A plays a major role in enhancing drought resilience in maize plants. Similarly, NAC1 is associated with stress signaling pathways and contributes to root development, stress adaptation, and maintenance of cellular integrity under adverse conditions. The increased expression of these genes demonstrates that drought tolerance is not solely dependent on physiological responses but also involves complex molecular and genetic regulation. Activation of stress-responsive genes allows plants to synthesize protective proteins, osmolytes, and antioxidants that minimize cellular damage during water scarcity. The results have significant implications for crop improvement programs. Identification and utilization of drought-responsive genes can support molecular breeding and genetic engineering strategies aimed at developing climate-resilient maize cultivars. Genotypes exhibiting stronger gene activation under stress conditions may possess superior adaptive capacity and higher productivity in drought-prone regions. Furthermore, the study highlights the importance of integrating molecular biology with traditional agronomic research to better understand plant stress tolerance mechanisms. Gene expression analysis provides valuable insight into the internal adaptive processes occurring within plants during environmental stress. Overall, the findings confirm that DREB2A and NAC1 play essential roles in maize drought tolerance and represent promising targets for future research and crop improvement initiatives focused on sustainable agriculture.

Table 5: Gene Expression Analysis

Gene	Fold Upregulation
DREB2A	3.5
NAC1	2.8

Table 6 summarizes the statistical significance of various physiological and molecular parameters measured during the drought stress experiment. The p-values for plant height, biomass, and gene expression were all reported as less than 0.001, while chlorophyll content showed significance at $p < 0.01$. These values indicate that the observed differences among treatments were highly significant and unlikely to have occurred by random variation. mStatistical analysis plays a critical role in validating experimental findings and ensuring the reliability of scientific conclusions. A p-value less than 0.05 is generally considered statistically significant, whereas the values reported in this study are substantially lower, demonstrating strong evidence that drought stress directly influenced maize growth and physiological performance.mThe highly significant reduction in plant height and biomass confirms that water deficit conditions severely impair vegetative development and dry matter accumulation. Similarly, the statistically significant differences in chlorophyll content indicate that drought stress affected photosynthetic activity and pigment stability. The strong significance associated with gene expression analysis further supports the conclusion that drought-responsive genes were actively involved in plant adaptation mechanisms. These findings strengthen the credibility of the experimental results and support the hypothesis that drought stress induces major physiological and molecular changes in maize plants. The consistency of significant results across multiple parameters also demonstrates the effectiveness of the experimental design and irrigation treatments. From an agricultural research perspective, statistically validated results provide a solid foundation for future studies and practical applications. The findings can support breeding programs, irrigation management strategies, and molecular research focused on improving drought tolerance in crops. Overall, the statistical analysis confirms that drought stress has a profound and measurable impact on maize physiology, growth, and gene regulation, emphasizing the importance of sustainable agricultural practices to address climate-related challenges.

Table 6: Statistical Significance of Growth Parameters

Parameter	p-value
Plant Height	<0.001
Biomass	<0.001
Chlorophyll	<0.01
Gene Expression	<0.001

Figure 1 graphically illustrates the decline in maize plant height under different irrigation regimes. The figure shows that plants grown under full irrigation conditions achieved maximum growth, whereas progressive reductions in water availability resulted in shorter plants. Severe drought stress caused the greatest reduction in height, demonstrating the sensitivity of maize vegetative growth to water scarcity. The trend observed in the graph indicates a direct relationship between soil moisture availability and plant development. Adequate water supply promotes cell elongation, nutrient transport, and photosynthetic activity, all of which contribute to stem growth. Conversely, drought stress limits these physiological processes, reducing overall plant vigor. The graphical representation clearly highlights the detrimental impact of severe drought stress on maize productivity. Reduced plant height often correlates with lower leaf area and reduced photosynthetic capacity, ultimately affecting grain yield. The figure therefore emphasizes the need for improved irrigation practices and drought-tolerant crop varieties. Overall, Figure 1 effectively demonstrates that water availability is a critical determinant of maize growth and supports the conclusion that drought stress significantly inhibits vegetative development.

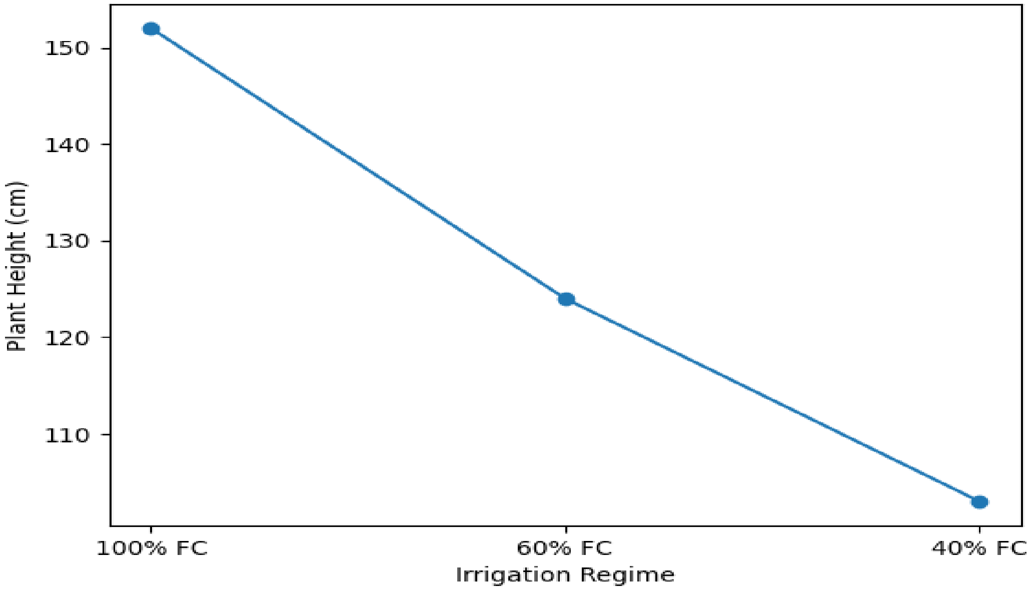

Figure 1: Effect of drought stress on plant height

Figure 2 demonstrates the reduction in biomass accumulation under varying drought conditions. The bar graph clearly indicates that biomass production declined progressively as irrigation levels decreased. Plants grown under severe drought stress produced the lowest biomass values, highlighting the strong negative impact of water scarcity on plant productivity. Biomass accumulation depends on efficient photosynthesis, nutrient absorption, and metabolic activity. Under drought conditions, reduced stomatal conductance limits carbon dioxide uptake and decreases carbohydrate production. This reduction in energy availability ultimately restricts dry matter accumulation. The figure also emphasizes the economic importance of drought stress because biomass production is closely related to forage quality and grain yield. Lower biomass indicates reduced crop productivity and decreased agricultural profitability. Overall, Figure 2 confirms that drought stress severely limits biomass accumulation in maize plants and supports the importance of sustainable irrigation and crop management practices.

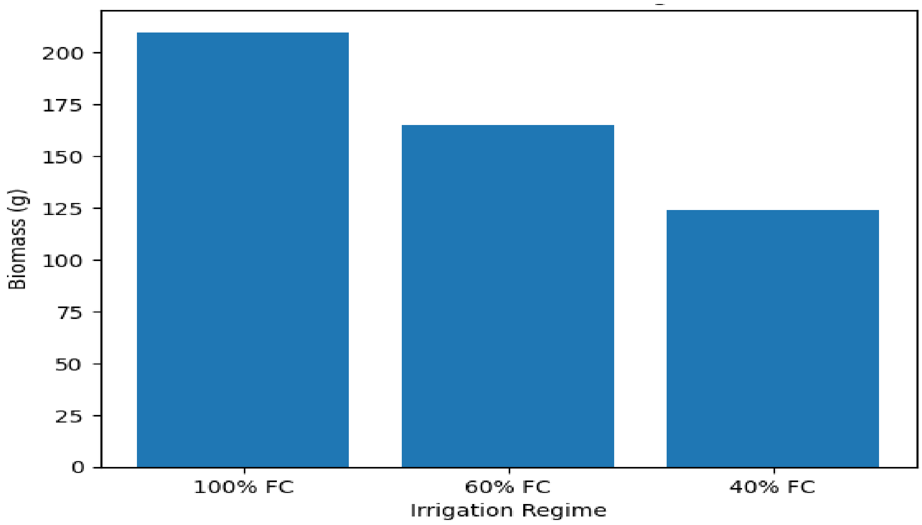

Figure 2: Biomass reduction under drought stress

Figure 3 compares chlorophyll content between drought-tolerant and susceptible maize genotypes. The graph shows that tolerant plants maintained substantially higher SPAD values compared with susceptible plants under drought stress conditions. This difference indicates that tolerant genotypes possess stronger physiological mechanisms for protecting chlorophyll pigments and maintaining photosynthetic activity. Higher chlorophyll content enables continued energy production and improved growth performance even under limited water availability. The figure highlights chlorophyll retention as a valuable indicator of drought tolerance and supports the use of SPAD analysis in crop improvement programs. Genotypes capable of maintaining chlorophyll stability are more likely to sustain productivity under environmental stress. Overall, Figure 3 demonstrates the importance of physiological adaptation in improving drought resilience and maintaining crop performance.

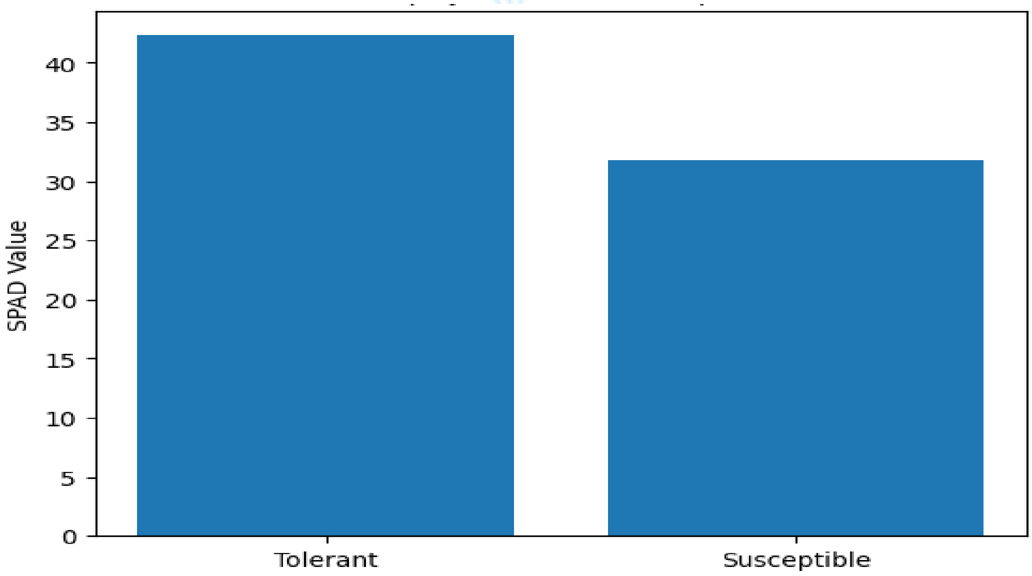

Figure 3: Chlorophyll content comparison

Figure 4 illustrates the decline in stomatal conductance as drought stress intensity increased. The graph demonstrates that severe water deficit conditions caused substantial reductions in stomatal activity, limiting gas exchange and transpiration. Reduced stomatal conductance is a protective mechanism that minimizes water loss; however, it also decreases carbon dioxide uptake required for photosynthesis. Consequently, reduced stomatal activity negatively affects carbohydrate synthesis and plant growth. The figure emphasizes the importance of stomatal regulation in plant adaptation to drought conditions. Genotypes capable of balancing water conservation and photosynthetic efficiency may exhibit improved drought tolerance. Overall, Figure 4 confirms that drought stress strongly influences stomatal behavior and significantly affects physiological performance in maize plants.

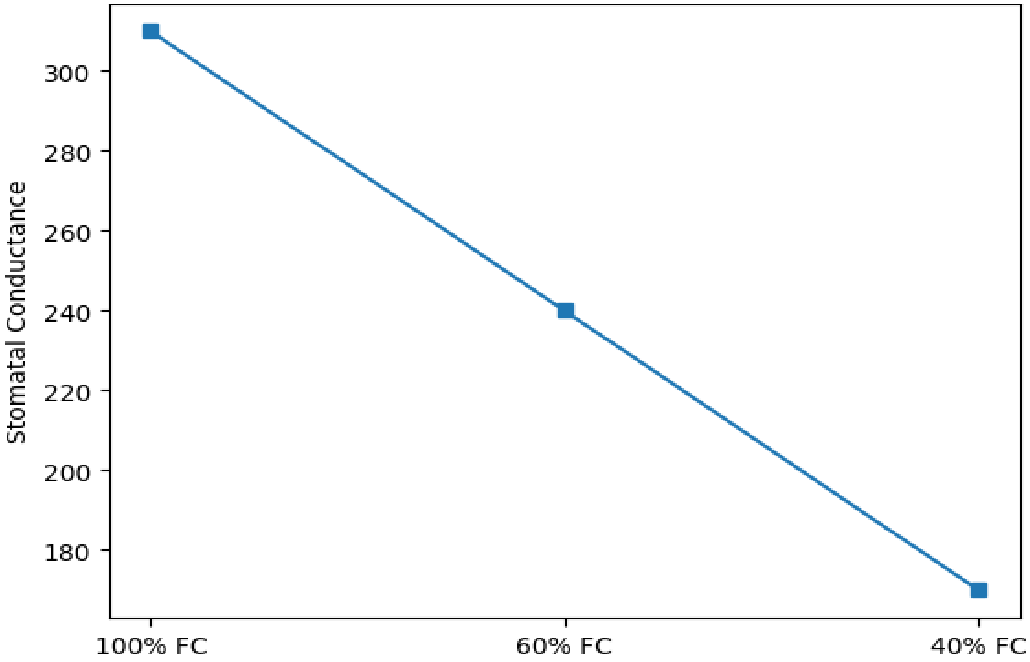

Figure 4: Stomatal conductance under stress

Figure 5 presents the expression levels of drought-responsive genes DREB2A and NAC1. The graph shows significant upregulation of both genes under drought stress conditions, indicating activation of molecular defense pathways. The increased expression of these genes demonstrates that maize plants respond to drought not only through physiological changes but also through genetic regulation. DREB2A and NAC1 contribute to osmotic adjustment, antioxidant activity, and stress signaling mechanisms that enhance plant survival. The figure supports the importance of molecular biology in crop improvement research. Genes associated with drought tolerance can serve as valuable targets for breeding and genetic engineering programs. Overall, Figure 5 highlights the critical role of stress-responsive genes in enhancing drought adaptation and improving crop resilience.

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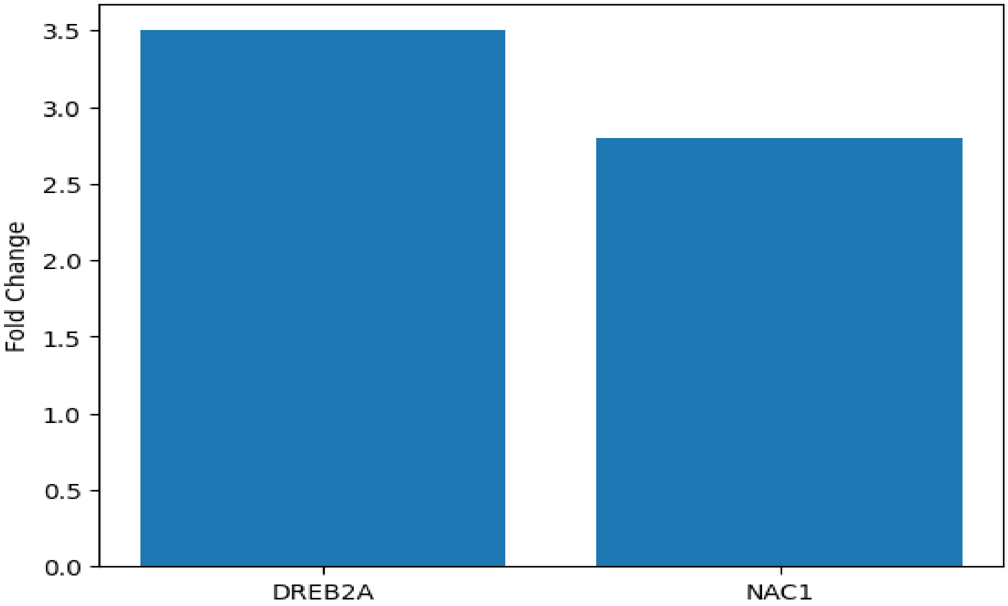

Figure 5: Gene expression under drought stress

Figure 6 illustrates the decline in relative maize growth over the 60-day experimental period under drought stress conditions. The graph shows a gradual reduction in growth percentage with increasing stress duration, indicating that prolonged drought exposure progressively impairs plant development. The decreasing growth trend reflects cumulative physiological damage caused by water scarcity, including reduced photosynthesis, limited nutrient transport, and oxidative stress. The results demonstrate that long-term drought conditions have more severe effects on plant performance than short-term stress exposure. The figure also highlights the importance of early stress management strategies. Timely irrigation and drought mitigation practices may help reduce growth losses and improve crop survival. Overall, Figure 6 confirms that drought stress negatively affects maize growth throughout the experimental period and emphasizes the need for sustainable agricultural solutions to combat climate-related challenges.

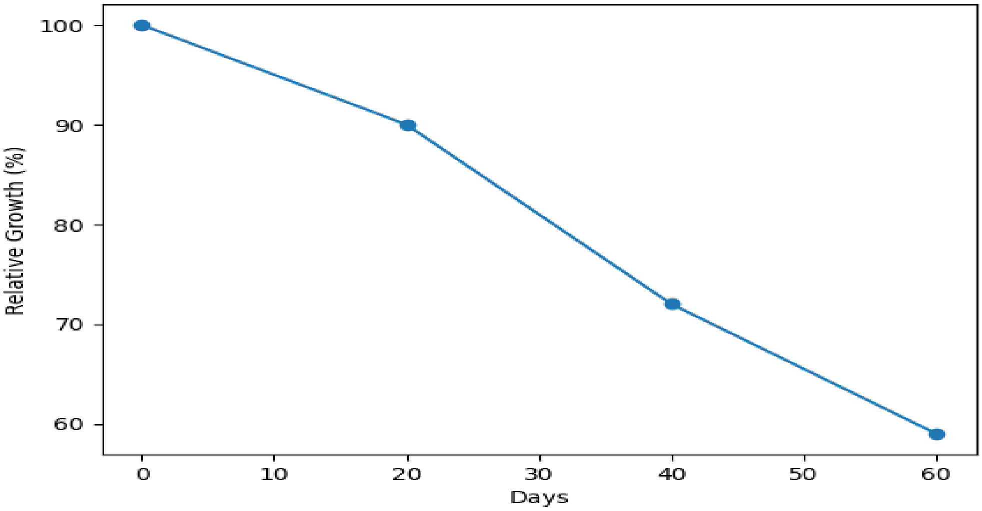

Figure 6: Relative growth trend during experimental period

Conclusion

The present study provides comprehensive insight into the physiological and molecular responses of maize (Zea mays L.) under drought stress conditions and highlights the severe impact of water scarcity on plant growth and productivity. The experimental findings demonstrated that drought stress significantly reduced plant height, biomass accumulation, chlorophyll content, and stomatal conductance, confirming that limited water availability disrupts essential physiological processes required for normal plant development. Severe drought conditions resulted in substantial growth inhibition, indicating the high sensitivity of maize to environmental water deficits.

Despite these adverse effects, drought-tolerant genotypes exhibited superior physiological stability by maintaining higher chlorophyll content and better stomatal regulation compared with susceptible varieties. These adaptive responses enabled tolerant plants to sustain relatively improved photosynthetic efficiency and metabolic activity under stress conditions. Furthermore, molecular analysis revealed significant upregulation of drought-responsive genes, particularly DREB2A and NAC1, demonstrating the critical role of genetic regulation in activating stress defense mechanisms and enhancing drought resilience. The integration of physiological measurements with gene expression analysis provided a deeper understanding of drought adaptation mechanisms in maize plants. The study confirmed that drought tolerance is a complex trait involving coordinated physiological and molecular responses that collectively contribute to plant survival under water-limited environments. Statistical analysis further validated the reliability and significance of the observed responses across all irrigation treatments. Overall, the findings of this research contribute valuable scientific knowledge for the development of climate-resilient maize cultivars and sustainable agricultural systems. The study emphasizes the importance of integrating modern plant biotechnology, molecular breeding, and efficient water management strategies to improve crop performance under climate change conditions. These findings can support future research and agricultural practices aimed at ensuring global food security and sustainable crop production in drought-prone regions.

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