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# Drought stress effects on quality and grain composition in four hybrid maize varieties with different stomatal resistance

## Farklı stoma direncine sahip dört hibrit mısır çeşitinde kuraklık stresinin verim ve tane bileşimi üzerine etkisi

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**Keywords:** Canopy temperature, crude ash, crude fiber, starch

**Anahtar sözcükler:** Kanopi sıcaklığı, ham kül, ham lif, nişasta

## ABSTRACT

**Objective:** This study aimed to evaluate transpiration and its effects on grain quality in some maize hybrids under drought stress conditions.

**Material and Methods:** The experiment was conducted using three irrigation levels-60 mm (control), 90 mm (moderate drought stress), and 120 mm (severe drought stress) of evaporation from a class A pan-applied to four maize hybrids: KSC 703, KSC 704, KSC 705, and KSC 706. This study was set up with three replications, carried out at Seed and Plant Improvement Institute (SPII), Karaj, Iran during 2015 and 2016 growing seasons.

**Results:** The results indicated that under drought stress conditions, the levels of crude fiber and ash increased, while starch content decreased. The KSC 706 hybrid exhibited the lowest stomatal resistance and canopy temperature, and the highest grain starch content, averaging 64.84%. These findings suggest that increased stomatal opening and transpiration are associated with improved maize grain quality.

**Conclusion:** Based on the findings, in regions where irrigation water is available and a higher starch content in grain is a priority, the KSC 706 hybrid is recommended.

## ÖZ

**Amaç:** Bu çalışma, kuraklık stresi koşullarında bazı hibrit mısır çeşitlerinde transpirasyonu ve bunun tane kalitesine etkisini değerlendirmek amacıyla yürütülmüştür..

**Materyal ve Yöntem:** Araştırma, dört farklı hibrit mısır çeşiti (KSC 703, KSC 704, KSC 705 ve KSC 706) kullanılarak, A sınıfı buharlaşma kabından uygulanan üç farklı sulama düzeyinde — 60 mm (kontrol), 90 mm (orta düzey kuraklık stresi) ve 120 mm (şiddetli kuraklık stresi) — yürütülmüştür. Deneme, İran'ın Karaj kentinde yer alan Tohum ve Bitki Islahı Enstitüsü (SPII)'nde 2015 ve 2016 yetiştirme sezonlarında üç tekerrürlü olarak kurulmuştur.

**Araştırma Bulguları:** Elde edilen sonuçlara göre, kuraklık stresi koşullarında ham selüloz ve kül içeriği artarken, nişasta oranı azalmıştır. KSC 706 melezi, en düşük stoma direnci ve kanopi sıcaklığı ile birlikte ortalama %64,84 ile en yüksek tane nişasta içeriğini göstermiştir. Bu bulgular, artan stoma açıklığı ve terlemenin, mısır tanelerinde kaliteyi artırıcı bir etkiye sahip olduğunu göstermektedir.

**Sonuç:** Araştırma bulgularına göre, sulama suyunun temin edilebilir olduğu ve yüksek tane nişasta içeriğinin öncelikli hedeflendiği bölgelerde, KSC 706 hibrit mısır çeşiti önerilmektedir.

## INTRODUCTION

Maize (*Zea mays*) is a highly versatile crop with significant global importance as both a food and feed grain (Bruns, 2003; Kavut & Soya, 2014). Depending on its intended use, maize can be classified into forage, grain, and industrial types (Qi et al., 2022). In the livestock industry, maize plays a critical role, particularly in the United States, where 90% of maize-based ethanol co-products are used as livestock feed (Wu & Munkvold, 2008). Poultry and ruminants, in particular, depend heavily on maize as a staple in their diets, consuming a substantial portion of the maize produced in countries like Pakistan (Habib et al., 2016). Beyond its use as fodder, maize is also a key ingredient in poultry feed, often substituting for other grains (Mumtaz et al., 2018).

On a global scale, the impacts of climate change are becoming increasingly evident, with rising temperatures and expanding aridity posing significant challenges to agriculture (Ghalkhani et al., 2022; Heydarzadeh et al., 2023). Insufficient water supply, particularly during critical growth and developmental stages, limits the ability of crops like maize to reach their full potential, ultimately reducing yield and impacting farmer livelihoods (Sallah et al., 2002). Water stress is a major limiting factor in semi-arid and arid regions, affecting all aspects of plant morphology, biology, growth, and yield (Heydarzadeh et al., 2022). It leads to a cascade of negative effects, including reduced crop maturation, impaired stomatal function, lower dry matter accumulation, diminished chlorophyll content, which leads to decreased photosynthetic efficiency (Bulgari et al., 2019). Drought stress not only hampers plant growth but also increases leaf and canopy temperatures by halting transpiration and increasing boundary layer resistance (Hirayama et al., 2006).

Soil water potential is one of the most crucial environmental factors for maize cultivation (Seydoşoğlu & Saruhan, 2017). A decline in soil water potential reduces relative water content, stomatal conductance, and CO2 availability, which in turn lowers photosynthesis in maize (Martinez et al., 2007). Reduced transpiration under water scarcity conditions leads to increased leaf temperature, disrupting the plant's cooling mechanisms (Yu et al., 2015). The transport of abscisic acid (ABA) to the leaves triggers leaf rolling, stomatal closure, and leaf senescence, sometimes even before a reduction in leaf turgor potential occurs through hydraulic mechanisms (Bharath et al., 2021). This root signaling helps the plant minimize water loss, a critical adaptation under drought conditions (Farooq et al., 2009).

Given maize's essential role in both human and animal diets, and its high per capita consumption in various countries, strategies to enhance both the quantitative and qualitative aspects of maize production are a priority in agricultural research (Cocks, 2003; Ghalkhani et al., 2022). Grain quality is a vital factor for producers and consumers alike, determining the final value of the crop (Ghorbanli et al., 2006). Optimal soil moisture during the grain development stage is crucial for starch and protein accumulation, which directly influences both yield and quality (Ahmadi & Baker, 2001). Water availability is particularly critical for maize grain quality, as water deficiency can increase the activity of enzymes involved in sucrose synthesis and carbohydrate branching, leading to enhanced carbohydrate synthesis under drought stress (Ghalkhani et al., 2022; Ghalkhani et al., 2023). Additionally, carbon stored in vegetative organs is transported to the grain during the filling period, further influencing grain quality (Ghorbanli et al., 2006).

This experiment aimed to evaluate the transpiration mechanisms in four maize hybrids under drought stress conditions and to assess how these mechanisms affect grain quality.

## MATERIALS and METHOD

### Experimental area and design

This study was conducted at the Seed and Plant Improvement Institute (SPII) located in Karaj during the 2015 and 2016 growing seasons. The experimental site is situated at an altitude of 1321 meters above sea level, at a latitude of 35° 48′ N and longitude of 51° E. The area has an average annual rainfall of 275 mm, characterized by cold winters and low precipitation, typical of semi-arid regions. The soil at the experimental site was sandy-clay with a bulk density of 1.36 g $cm^{-3}$, a pH of 7.5, electrical conductivity of 0.7 dS $m^{-1}$, and a field capacity of 26%. Field preparation included plowing, discing, and leveling with a spring leveler. Prior to planting, 99 kg $ha^{-1}$ of pure nitrogen and 144 kg $ha^{-1}$ of phosphorus were applied in the form of urea and ammonium phosphate, respectively. An additional 92 kg $ha^{-1}$ of pure nitrogen from urea was applied as a top-dressing fertilizer during the growing season. The experiment was arranged as a factorial based on a randomized complete block design with three replications. Three irrigation levels—irrigation after 60, 90, and 120 mm of evaporation from a class A pan—were applied to four maize hybrids: KSC 703, KSC 704, KSC 705, and KSC 706.

**Field management and irrigation system**

A furrow irrigation system was used, with furrows spaced 75 cm apart and plants spaced 18 cm apart within rows, resulting in a planting density of 85,000 plants $ha^{-1}$. Each experimental plot consisted of five planting rows, each 6 meters in length. Weed control was managed with the application of Eradicane herbicide (6 L $ha^{-1}$) before planting and mechanical control during the V4-V6 growth stages. For pest management, Larvin pesticide was applied at a rate of 1 kg $ha^{-1}$ during the V4-V6 stages to control Spodoptera and Agrotis pests.

Drought stress treatments commenced after the V2-V3 growth stages. Prior to this stage, normal irrigation was implemented after 60 mm of evaporation to ensure complete plant establishment. To schedule subsequent irrigations, daily pan evaporation was recorded at 9:00 A.M. The required irrigation volume was calculated based on soil moisture content, which was determined by sampling soil up to the depth of root development and assessing the moisture levels. The irrigation water volume (V) was calculated using the Equations 1 and 2 (Afshar et al., 2014; Farhadi et al., 2022):

$$H = \rho b \times (\theta_{FC} - \theta_m) \times D \quad (1)$$

$$V = H \times A \quad (2)$$

In equations 1 and 2, $H$ represents the water height in the plot, $\rho b$ is the soil bulk density, $\theta_{FC}$ is the soil moisture at field capacity, $\theta_m$ is the soil moisture at the time of irrigation, $D$ is the root development depth, $V$ is the irrigation water volume in the plot, and $A$ is the plot area.

**Determination of physiological parameters**

Stomatal resistance (SR) was measured using a porometer (Delta-T Devices model) at three critical growth stages: V6-V7, pollination up to silk emergence, and the grain milky stage. Measurements were taken from the upper, middle, and lower sections of the ear leaf in six plants per plot. These plants were randomly selected at the V6-V7 stage and marked to ensure consistency in measurements across the subsequent stages. All measurements were conducted between 11:00 AM and 1:00 PM, a period chosen for its high solar radiation, optimizing the accuracy of the readings. Measurements were taken one day prior to irrigation at each growth stage. The porometer was calibrated using plates with six different pore diameters. Data obtained from the leaf measurements were then fitted to a regression line equation, facilitating the accurate calculation of stomatal resistance, expressed in s $cm^{-1}$.

Canopy temperature was measured at the ear leaf level using a laser infrared thermometer (TM_958 model) at three critical growth stages: V6-V7, pollination up to silk emergence, and the grain milky stage. These measurements were conducted from a distance of 1 meter in six randomly selected and marked plants per plot, between 11:00 AM and 1:00 PM. To ensure consistency, the same plants were used for measurements across all stages. For accurate calculation of canopy temperature depression (CTD), simultaneous air temperature measurements were taken alongside canopy temperature readings. Air temperature was measured using a calibrated digital thermometer with a shielded sensor to minimize direct solar radiation effects. The sensor was positioned at the same height as the canopy and placed 1 meter away from the plants to avoid any influence from plant transpiration. This method ensures that the air temperature accurately reflects the ambient conditions surrounding the canopy. Measurements at each growth stage were taken one day before irrigation to maintain consistent soil moisture levels. The CTD was then calculated as the difference between the measured air temperature and canopy temperature, providing a reliable indicator of plant stress and water status.

**Determination of grain yield and composition**

For the determination of grain yield, a 4.5 $m^2$ area from each plot was harvested, accounting for marginal effects. Grain composition, including crude fiber, crude ash, soluble sugar, crude protein, starch, crude fat, and dry matter, was analyzed using Near-Infrared Spectroscopy (NIR) with a DICKEY-john model device, a widely recognized and reliable method in agricultural and food quality analysis. For each plot, a 1 kg grain sample was randomly selected, milled, and a 5-gram portion of the milled sample was used for analysis. The NIR device was calibrated using standard coefficients, and qualitative indices were reported as percentages (Nicolia et al., 2007; Shao et al., 2009).

**Statistical analysis**

Data were analyzed as a combined two-year experiment after testing for homogeneity of variances using Bartlett's test. Variance analysis was performed using SAS software (version 9.1), and means were compared using Duncan's multiple range test at a 5% probability level.

## RESULT and DISCUSSION

**Stomatal resistance and canopy temperature**

The study observed notable differences in SR among various maize hybrids, particularly in KSC 706, compared to other hybrids during the vegetative stage up to pollination (Figure 1). KSC 705 exhibited higher SR than the other hybrids until the pollination stage, after which the resistance levels of KSC 705 converged with the others. During the grain milky stage, differences in the SR among the cultivars were minimal (Figure 1). The variation in the SR for KSC 706 followed a relatively linear trend, markedly distinct from the other hybrids. It exhibited a sharp increase during the pollination to grain milky stages, eventually aligning with the other hybrids (Figure 1). The decrease in the SR observed in KSC 706 during the vegetative stage likely facilitated stomatal opening until the grain milky stage, allowing for enhanced $CO_2$ assimilation and photosynthesis. However, this could also lead to increased moisture loss from the rhizosphere in this hybrid.

Under well-watered conditions (irrigation after 60 mm of evaporation), the SR was lowest during the vegetative stage (Figure 2). In this phase, the open stomata facilitated effective $CO_2$ assimilation and transpiration. However, as the plants transitioned to the pollination and reproductive stages, the SR began to increase, eventually reaching levels comparable to those observed under moderate drought stress by the grain milky stage (Figure 2). This increase suggests a reduction in stomatal guard cell flexibility as the plant undergoes senescence, leading to decreased stomatal opening, diminished $CO_2$ assimilation, and reduced apparent photosynthesis, with remobilization becoming a more prominent factor. The highest SR was recorded during the vegetative stage under severe drought stress conditions (Figure 2). Nonetheless, as the plant entered the senescence phase, stomatal guard cell flexibility decreased, resulting in reduced SR, even under severe drought stress, bringing the resistance levels closer to those observed under moderate drought stress and control conditions (Figure 2). The role of abscisic acid (ABA) as an early warning signal under declining moisture conditions in the rhizosphere is well-documented (Ghalkhani et al., 2023). ABA is transported from the roots to the shoots, initiating stomatal closure before a significant reduction in leaf turgor potential occurs (Zhang et al., 1987; Bharath et al., 2021).

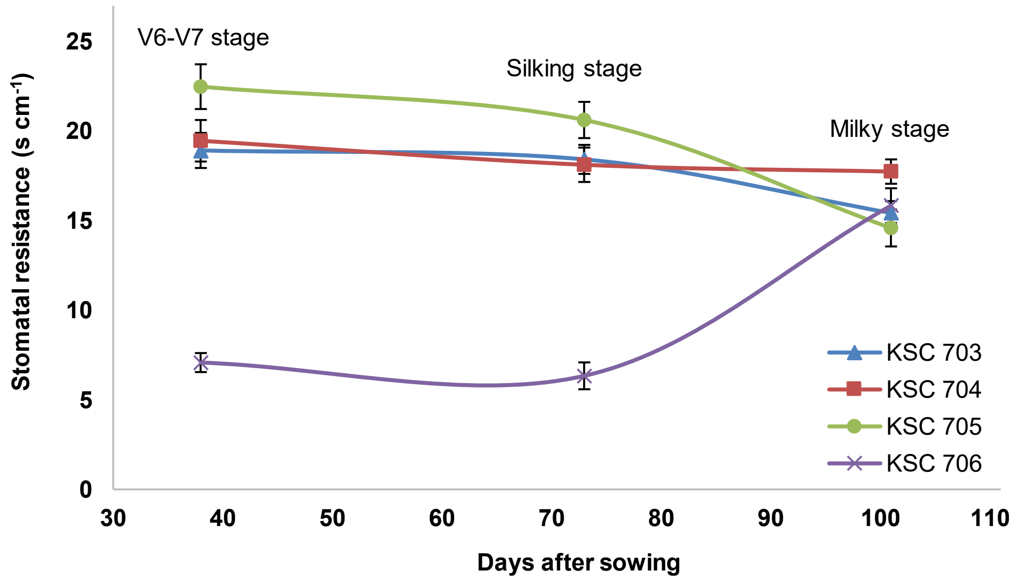


**Figure 1.** Stomatal resistance (s $cm^{-1}$) across different maize hybrids from the V6 to the milky stage.

***Şekil 1.*** *V6 döneminden süt olum evresine kadar farklı hibrit mısır çeşitlerinde stoma direnci (s cm* $^{-1}$*)*

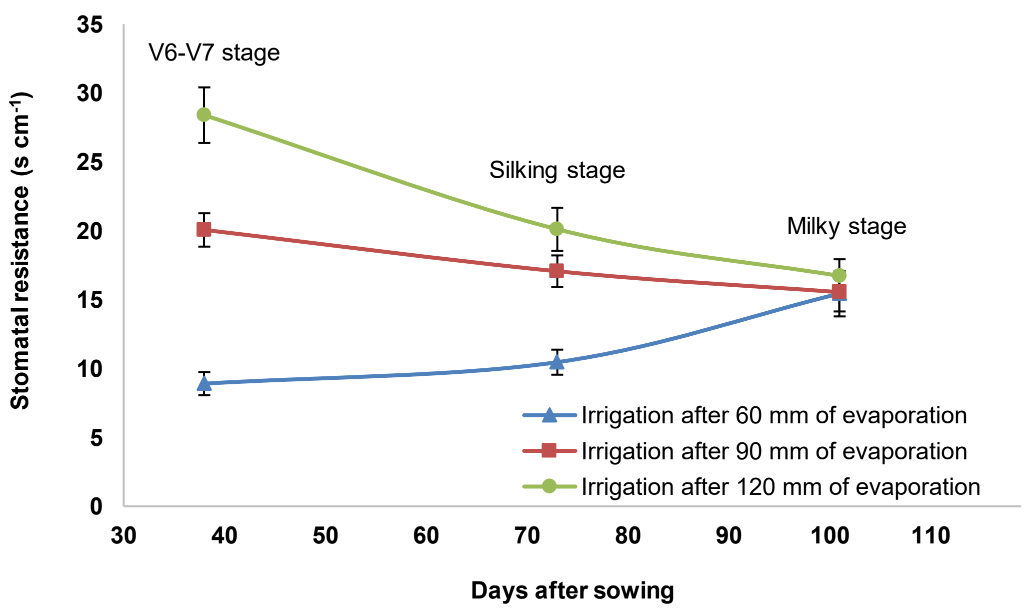


**Figure 2.** Stomatal resistance (s $cm^{-1}$) under varying drought stress conditions from the V6 to the milky stage.

***Şekil 2****. V6 gelişme döneminden süt olum evresine kadar farklı kuraklık stresi düzeylerinde ölçülen stoma direnci (s cm* $^{-1}$*)*

The relationship between the SR and CTD was evident, with CTD increasing as the SR decreased (Figures 1 & 3). As the SR rises and stomata close, transpiration decreases, leading to an increase in canopy temperature. KSC 706 exhibited the highest CTD, indicating the coolest canopy, likely due to its lower SR (Figure 3). This suggests that KSC 706 might not receive or respond to secondary drought stress signals, potentially due to differences in its hormonal signaling system, which allows stomata to remain open and the cooling transpiration process to continue until moisture in the rhizosphere is depleted.

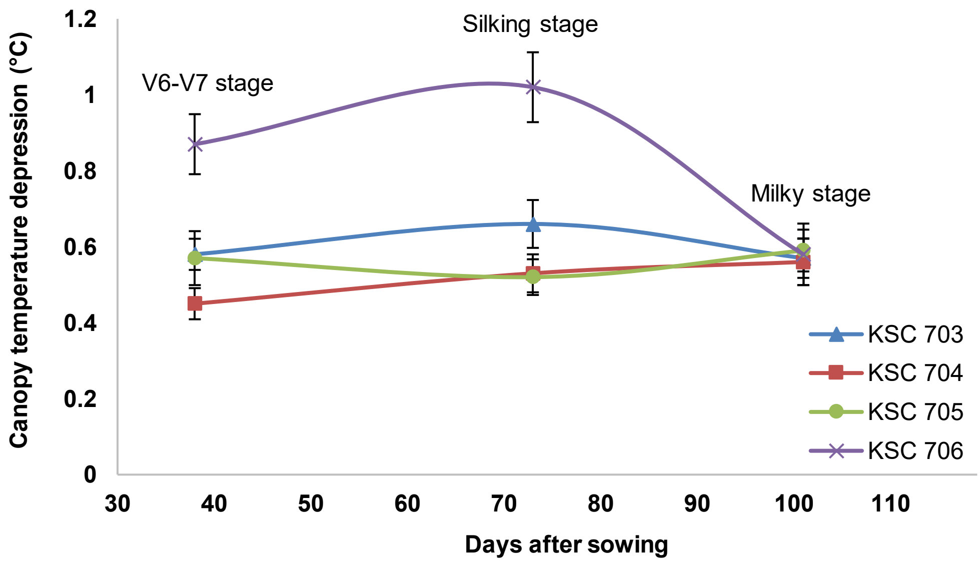


**Figure 3.** Canopy temperature depression (°C) in different maize hybrids from the V6 to the milky stage.

***Şekil 3.*** *V6 döneminden süt olum evresine kadar farklı hibrit mısır çeşitlerinde kanopi sıcaklık farkı (°C)*

The coolest canopy temperatures were recorded during the vegetative stage under control conditions (Figure 4), attributed to the ample moisture available to the roots, allowing stomata to remain open and sustain transpiration, leading to minimal canopy temperature (Figure 4). This cooling trend persisted until the pollination stage. However, during the grain milky stage, relative senescence and a loss of stomatal guard cell flexibility led to increased SR, stomatal closure, reduced transpiration, and an increase in CTD (Figure 4). Canopy temperature rose in response to the increase in SR under moderate and severe drought stress conditions (Figures 2 & 4). The synthesis of ABA in the roots and its transport to leaf cells via the xylem serves as an early warning system under drought stress, promoting stomatal closure before a decrease in leaf turgor potential is perceived (Farooq et al., 2009).

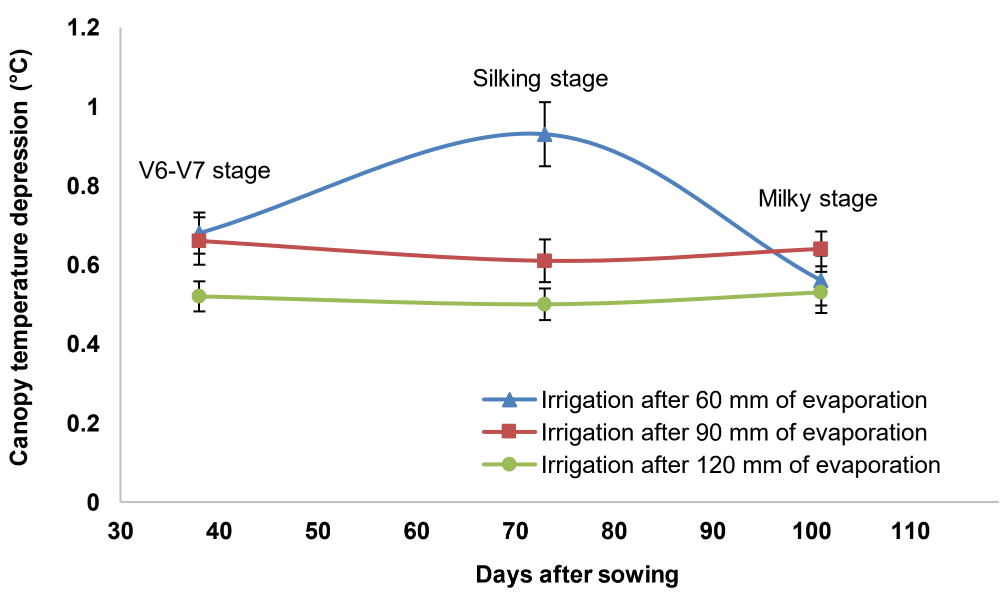


**Figure 4.** Canopy temperature depression (°C) under drought stress conditions from the V6 to the milky stage.

***Şekil 4.*** *V6 döneminden süt olum evresine kadar kuraklık stresi koşullarında kanopi sıcaklık farkı (°C)*

The differences observed in stomatal resistance and canopy temperature among maize hybrids highlight the physiological adaptations of these plants to varying environmental conditions, particularly under drought stress (Lepekhov, 2022). The lower SR in KSC 706 during the vegetative stage suggests a potential advantage in $CO_2$ assimilation and photosynthesis under optimal conditions, leading to more robust growth. However, this same trait might predispose the hybrid to greater water loss under drought conditions, as indicated by the linear increase in the SR during the reproductive stages. This pattern aligns with the concept of drought avoidance, where plants delay stomatal closure to maintain growth processes as long as possible, even at the cost of higher water use. In contrast, KSC 705's higher SR during early growth stages could be indicative of a conservative water use strategy, potentially making it more resilient under prolonged drought conditions. The convergence of SR levels among hybrids during the grain milky stage suggests a common physiological response to drought stress, possibly driven by hormonal signals such as ABA, which is known to mediate stomatal closure under water-deficit conditions (Bharath et al., 2021). The relationship between stomatal resistance and canopy temperature, as reflected in CTD, underscores the importance of transpiration in regulating plant temperature (Yu et al., 2015). The ability of KSC 706 to maintain a cooler canopy under control conditions points to its potential for higher efficiency in water use and thermoregulation, traits that are beneficial under optimal growing conditions but could be detrimental under drought stress if water availability becomes limiting. This balance between maintaining growth and conserving water is a critical factor in the overall drought tolerance of maize hybrids (Ghalkhani et al., 2023). The findings also emphasize the role of root-to-shoot signaling in drought response, with ABA playing a crucial role in initiating stomatal closure before significant water stress is perceived by the leaves (Farooq et al., 2009; Farhadi et al., 2022; Ghalkhani et al., 2023). This early signaling mechanism allows plants to conserve water during the initial stages of drought, potentially extending their survival under prolonged stress conditions.

**Grain quality (compositions)**

The effect of drought stress on crude fiber, crude ash, and starch was significant at the 5% probability level, whereas it was not significant on other quality traits (Table 1). Hybrid effects were significant only for starch at the 1% probability level (Table 1).

Under control conditions, the minimum crude fiber content, averaging 2.46%, was observed; however, under mid and severe drought stress conditions, crude fiber content increased significantly (Table 2). Similarly, the crude ash content also increased under drought stress conditions, with the minimum amount observed at 1.10% under normal irrigation (Table 2). Increased drought stress is associated with higher crude fiber content, which negatively impacts digestibility and overall grain quality (Pourali et al., 2023). The rise in insoluble fibers within cell walls under water deficit conditions is a plant's physiological adaptation to prevent moisture loss (Jahanzad et al., 2013). The application of irrigation helps slow this process, preventing a significant increase in crude fiber content (Jahansouz et al., 2014).

The increase in crude protein content under water stress, compared to normal irrigation conditions (Table 2), can be attributed to the shortened growth and development period induced by water stress. This shortened period results in a lower carbohydrate-to-protein ratio, thereby elevating the protein content (Heydarzadeh et al., 2022 Attaran Dowom et al. (2022) also observed that substantial amounts of soluble sugars accumulate during periods of water scarcity, which helps to mitigate the negative effects of moisture stress on crop yield. This accumulation of soluble sugars serves as a biochemical osmotic adjustment and represents a key defense mechanism in plants under water stress, helping to alleviate oxidative damage (Elshamly & Nassar, 2023).

Drought stress affected starch content, with the maximum starch content observed under control conditions, averaging 64.31% (Table 2). Under mid drought stress, starch content decreased slightly to 63.43%, which was not significantly different from control conditions, but under severe drought stress, it significantly decreased to 62.76% (Table 2). Previous research suggests that drought stress disrupts enzyme activity involved in starch biosynthesis, such as soluble starch synthase (SSS), leading to a reduction in starch accumulation in cereal grains (Kowles & Philips, 1988; Ghalkhani et al., 2022). The reduction in starch storage under severe drought stress conditions may be attributed to the disruption of SSS enzyme activity, which is crucial for converting sucrose into starch. Additionally, drought stress likely reduces the production of assimilates, particularly sucrose, leading to a lower availability of sucrose for starch synthesis.

**Table 1.** Combined analysis of variance for the effects of drought stress on grain quality in maize hybrids

***Çizelge 1.*** *Mısırda kuraklık stresinin tane kalitesi üzerindeki etkilerine ilişkin varyans analizi*

| SOV | df | Mean Squares | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Crude fiber | Crude ash | Soluble sugar | Crude protein | Starch | Crude fat | Grain dry matter |
| Year | 1 | 0.02 $^{ns}$ | 0.03 $^{*}$ | 0.056 $^{ns}$ | 65.76$^{**}$ | 826.48$^{**}$ | 4.87 $^{**}$ | 480.91 $^{**}$ |
| Block | 4 | 0.29 | 0.005 | 0.70 | 4.68 | 2.74 | 0.12 | 203.04 |
| Drought stress | 2 | 0.26$^{*}$ | 0.01 $^{*}$ | 0.50 $^{ns}$ | 4.75 $^{ns}$ | 14.39 $^{*}$ | 0.06 $^{ns}$ | 58.01 $^{ns}$ |
| year × Drought stress | 2 | 0.06 $^{ns}$ | 0.01 $^{ns}$ | 2.35 $^{*}$ | 1.56 $^{ns}$ | 1.38 $^{ns}$ | 0.02 $^{ns}$ | 54.56 $^{ns}$ |
| Hybrid | 3 | 0.05 $^{ns}$ | 0.005 $^{ns}$ | 1.00 $^{ns}$ | 2.04 $^{ns}$ | 15.95 $^{**}$ | 0.006 $^{ns}$ | 40.24 $^{ns}$ |
| Year × Hybrid | 3 | 0.06 $^{ns}$ | 0.005 $^{ns}$ | 0.07 $^{ns}$ | 0.46 $^{ns}$ | 1.86 $^{ns}$ | 0.13 $^{ns}$ | 21.34 $^{ns}$ |
| Hybrid × Drought stress | 6 | 0.03 $^{ns}$ | 0.002 $^{ns}$ | 0.60 $^{ns}$ | 1.02 $^{ns}$ | 3.13 $^{ns}$ | 0.05 $^{ns}$ | 39.96 $^{ns}$ |
| Year × Hybrid × Drought stress | 6 | 0.08 $^{ns}$ | 0.009 $^{ns}$ | 0.92 $^{ns}$ | 3.02 $^{ns}$ | 10.49 $^{ns}$ | 0.12 $^{ns}$ | 79.07 $^{ns}$ |
| Error | 44 | 0.1 | 0.006 | 0.74 | 2.39 | 3.63 | 0.06 | 59.71 |

**Table 2.** Mean comparison of grain quality in maize hybrids as affected by drought stress

***Çizelge 2.*** *Kuraklık stresinden etkilenen hibrit mısır çeşitlerinde tane kalitesine ilişkin ortalama karşılaştırması*

| Experimental factors | Crude fiber (%) | Crude ash (%) | Soluble sugar (%) | Crude protein (%) | Starch (%) | Crude fat (%) | Grain dry matter (%) |
|---|---|---|---|---|---|---|---|
| Irrigation Regime | | | | | | | |
| 60 mm | 2.46±0.073$^{b}$ | 1.10±0.033$^{b}$ | 4.17±0.305$^{a}$ | 9.73±0.854$^{a}$ | 64.31±1.199$^{a}$ | 1.18±0.580$^{a}$ | 85.76±2.833$^{a}$ |
| 90 mm | 2.66±0.098$^{a}$ | 1.16±0.044$^{a}$ | 4.36±0.269$^{a}$ | 10.44±0.821$^{a}$ | 63.43±0.987$^{ab}$ | 1.70±0.687$^{a}$ | 88.54±3.356$^{a}$ |
| 120 mm | 2.57±0.110$^{ab}$ | 1.13±0.045$^{ab}$ | 4.45±0.311$^{a}$ | 10.55±0.960$^{a}$ | 62.76±1.266$^{b}$ | 1.75±0.709$^{a}$ | 88.31±3.027$^{a}$ |
| Hybrid | | | | | | | |
| KSC 703 | 2.52±0.159$^{a}$ | 1.11±0.051$^{a}$ | 4.47±0.510$^{a}$ | 9.58±1.168$^{a}$ | 62.99±1.035$^{b}$ | 1.76±0.122$^{a}$ | 86.85±4.561$^{a}$ |
| KSC 704 | 2.56±0.166$^{a}$ | 1.15±0.057$^{a}$ | 4.58±0.559$^{a}$ | 10.62±1.382$^{a}$ | 62.73±1.111$^{b}$ | 1.73±0.074$^{a}$ | 89.04±5.554$^{a}$ |
| KSC 705 | 2.64±0.160$^{a}$ | 1.14±0.063$^{a}$ | 4.17±0.545$^{a}$ | 10.39±1.346$^{a}$ | 63.45±1.093$^{b}$ | 1.78±0.129$^{a}$ | 88.52±4.535$^{a}$ |
| KSC 706 | 2.52±0.144$^{a}$ | 1.13±0.059$^{a}$ | 4.09±0.499$^{a}$ | 10.09±1.207$^{a}$ | 64.84±1.361$^{a}$ | 1.74±0.082$^{a}$ | 85.80±5.039$^{a}$ |
| Year | | | | | | | |
| 2015 | 2.55±0.082$^{a}$ | 1.11±0.023$^{b}$ | 4.24±0.241$^{a}$ | 9.28±0.703$^{b}$ | 66.89±1.237$^{a}$ | 2.01±0.210$^{a}$ | 84.97±3.705$^{b}$ |
| 2016 | 2.58±0.097$^{a}$ | 1.15±0.029$^{a}$ | 4.41±0.320$^{a}$ | 11.2±0.871$^{a}$ | 60.11±1.288$^{b}$ | 1.49±0.184$^{b}$ | 90.14±3.100$^{a}$ |

Means, in each column and for each factor, followed by at least one letter in common are not significantly different at the 5% probability level- using Duncan's Multiple Range Test

Among the maize hybrids studied, KSC 706 exhibited the highest starch content, averaging 64.84% (Table 2). This may be due to lower SR and higher transpiration rates in KSC 706 from the V6 stage up to silk emergence (Figure 1). The efficient water transport from the roots to the shoots and subsequent transpiration cooling likely maintained optimal canopy temperatures in this hybrid (Figure 3), allowing the enzymes responsible for converting sucrose into starch to function effectively. This continuous enzyme activity under favorable conditions resulted in the highest starch production in KSC 706.

Water stress, often resulting from drought, is recognized as one of the major ecological challenges facing agriculture. Drought stress exerts significant impacts on plants at various levels, from cellular to whole-plant structures, affecting their structural, biological, and molecular characteristics (Baghdadi et al., 2023). It limits plant growth and development by disrupting several physiological processes, including nutrient absorption, stomatal function, transpiration rate, sugar synthesis, and photosynthesis (Bukhari et al., 2022). The severity and duration of water stress significantly influence how crops respond, affecting their overall resilience and productivity (Heydarzadeh et al., 2022).

In this study, maize grain productivity was notably reduced under water stress conditions, likely due to decreased assimilation of photosynthetic carbon, which is essential for determining crop yield. The stress led to suppressed leaf growth and development, induced leaf senescence, stomatal closure, and a reduction in carbon fixation efficiency (Elshamly & Nassar, 2023). The decline in seed and biomass yield under water stress can be attributed to reduced moisture uptake, impaired photosynthesis, and diminished hormone production and enzyme activity (Elshamly et al., 2024).

The correlation analysis revealed a strong negative relationship between stomatal resistance and canopy temperature depression (r = -0.951, $p < 0.01$) (Figure 5), highlighting the significant role of stomatal regulation in heat stress management. As SR increased, CTD decreased, indicating that maize hybrids with higher stomatal resistance experienced more canopy heating, likely due to reduced transpiration. This finding aligns with previous research showing that elevated stomatal resistance limits transpiration and canopy cooling, particularly under drought conditions (Lhomme, 2001; Gong et al., 2023). In relation to grain quality traits, SR showed a positive correlation with soluble sugar (r = 0.684) and dry matter content (r = 0.853, $p < 0.05$) (Figure 5). This suggests that plants with higher SR accumulate more sugars and dry matter, likely as an adaptive response to water stress. Soluble sugars may serve as osmotic regulators, helping plants maintain cell turgor under drought conditions (Baghdadi et al., 2023). Conversely, SR was strongly negatively correlated with starch content (r = -0.927, $p < 0.01$) (Figure 5), indicating a metabolic shift where stressed plants prioritize soluble sugar retention over starch synthesis. Such carbohydrate adjustments are well-documented in crops exposed to water deficits, where sugars play a crucial role in maintaining osmotic balance and protecting cellular structures (Pourali et al., 2023; Tavazoh et al., 2024). CTD also exhibited significant correlations with grain quality traits, particularly a strong positive correlation with starch content (r = 0.957, $p < 0.01$) (Figure 5).

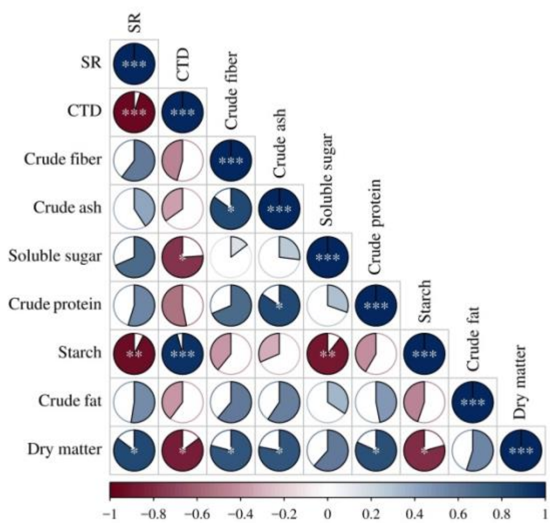


**Figure 5.** Pearson correlation analysis of stomatal resistance (SR), canopy temperature depression (CTD), and various quality traits in maize

***Şekil 5.*** *Mısırda stoma direnci (SR), gözenek sıcaklık farkı (CTD) ve çeşitli kalite özellikleri arasındaki Pearson korelasyon analizi*

This suggests that hybrids with more efficient canopy cooling tend to accumulate more starch. Other grain quality traits revealed some notable associations. Crude fiber was positively correlated with crude ash, and crude protein was strongly correlated with crude ash (Figure 5), suggesting a connection between mineral content and protein levels in the grain. Grain dry matter was also positively correlated with both crude fiber and crude protein, indicating that hybrids with higher dry matter content tend to exhibit better nutritional quality (Ghalkhani et al., 2022). In summary, the correlations between SR, CTD, and grain quality traits suggest that maize hybrids exhibit distinct physiological and metabolic responses to drought stress. These findings have important implications for breeding programs aimed at improving drought tolerance while maintaining grain quality. By selecting hybrids that balance stomatal regulation, canopy cooling efficiency, and grain quality across varying irrigation regimes, breeders can develop maize varieties that are better suited to water-limited environments. Further research is needed to explore the genetic mechanisms underlying these relationships and to confirm their stability across different environmental conditions.

## CONCLUSION

The results indicate that KSC 706, with its lower stomatal resistance and efficient transpiration cooling system, is better suited to environments where water is available and higher starch production is desired. This hybrid's ability to maintain open stomata and regulate canopy temperature effectively underpins its superior performance in starch accumulation. Therefore, KSC 706 can be recommended for cultivation in regions with adequate irrigation, where maximizing starch yield is a primary objective. Additionally, the strong negative correlation between stomatal resistance and canopy temperature depression, along with their relationships to grain quality traits, highlights the importance of stomatal regulation and canopy cooling in maize's adaptive response to drought stress. These findings provide valuable insights for breeding programs focused on enhancing both drought resilience and grain quality in water-limited environments.

**Data Availability**

Data will be made available upon reasonable request.

**Author Contributions**

Conception and design of the study: AM, FG, VG, EK, SH; sample collection: AM, FG, VG, SH; analysis and interpretation of data: AM, FG, VG, SH; statistical analysis: AM, FG, VG, EK, SH; visualization: AM, FG, VG, SH; writing manuscript: AM, FG, VG, EK, SH, MS

**Conflict of Interest**

The authors have no conflicts of interest to declare.

**Ethical Statement**

I declare that there is no need for an ethics committee for this research.

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