



RESEARCH ARTICLE

Moisture stress induced changes in growth, physiology and productivity of maize: An experimental evaluation

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Abstract

Water deficit is a major constraint for maize production, demanding irrigation approaches that increase water use efficiency while reducing yield losses. The present study evaluated the effect of moisture stress induced at different growth stages on the growth, physiological functions, yield characteristics and productivity of maize. The experiment consisted of 10 irrigation treatments, involving a well-watered control (T1- 0.75 irrigation water/cumulative pan evaporation (IW/CPE) throughout the crop period) and moisture stress imposed at vegetative, reproductive and maturity stages with 0.375 IW/CPE ratio. Among the moisture stress treatments, moderate stress 2 (T7) (0.75 IW/CPE up to 85 DAS and 0.375 IW/CPE from 85 days after sowing (DAS) to harvest) consistently outperformed the other stress treatments and remained statistically comparable with the well-watered control (T1) with higher plant height (190.93 and 192.43 cm), leaf area index (LAI) (5.60 and 5.80), total chlorophyll content (1.64 and 1.58 mg g⁻¹ FW) and lower proline content (0.61 and 0.69 mg g⁻¹ FW) and this improved growth and physiological performance was reflected in superior cob length, grain number and cob weight, which ultimately resulted in higher grain yields of 7794 and 7283 kg ha⁻¹ during summer 2025 and 2026, respectively. However, severe moisture stress imposed during critical growth stages resulted in a substantial reduction in growth, physiological functions and yield. The findings revealed that a moderate stress strategy induced in the mid-growth stage can sustain maize productivity while reducing irrigation demand, making it a promising approach for improving water use efficiency and enhancing climate resilience in maize production.

Keywords: deficit irrigation; drought; maize; moderate stress; total chlorophyll; water use efficiency

Introduction

Maize (*Zea mays* L.) is one of the most versatile and widely cultivated cereal crops in the world, owing to its broad adaptability to diverse agro-climatic conditions and high genetic yield potential. Often referred to as the “Queen of Cereals” or the “Miracle Crop,” maize ranks third among cereal crops after rice and wheat in terms of global production (1). Globally, maize is cultivated in approximately 213.7 million ha across more than 170 countries, producing about 1312.6 million tonnes with an average productivity of 6.14 t ha⁻¹. In India, it is cultivated in 13.0 million ha with a production of 46.2 million tonnes (2). In Tamil Nadu, maize occupies approximately 0.41 million ha with a production of 2.84 million tonnes and an average productivity of 6917 kg ha⁻¹ during 2024–25 (3).

Drought affects nearly one-third of the world's population and is regarded as one of the most hazardous abiotic stresses limiting crop production globally (4). Despite its high yield potential, maize productivity is frequently constrained by abiotic stresses,

among which drought or moisture stress is considered the most severe. The changing climate pattern worldwide projects drought and heat stress as major threats to maize cultivation, resulting in an estimated decline of global maize production by 15–20 % annually (5, 6).

Moisture stress adversely affects several physiological and biochemical processes in maize. Drought decreases photosynthetic pigments such as chlorophyll and carotenoids, thereby impairing photosynthetic efficiency and biomass accumulation (7). Under moderate water stress, the photosynthetic rate may remain relatively stable despite reductions in carboxylation efficiency; however, severe moisture deficits significantly reduce both photosynthetic rate and CO₂ concentration at the site of carboxylation (8). Drought-induced water deficits also promote the accumulation of reactive oxygen species (ROS), which cause oxidative damage by restricting stomatal opening, accelerating photoreduction of oxygen within chloroplasts and increasing photorespiration (9). Consequently, variations in chlorophyll content

and leaf water status can serve as important indicators of drought stress and plant tolerance. Despite being a thermophilic crop with an optimum growth temperature of approximately 28 °C, maize seedlings are highly sensitive to drought during emergence and early growth stages; this stress negatively affecting photosynthesis, nutrient uptake, nutrient remobilisation, vegetative growth, plant height, leaf area development, ear formation and ultimately grain yield (10, 11).

Among growth-related traits, plant height and leaf area index (LAI) are particularly important indicators of crop performance under moisture stress. Plant height is closely associated with crop productivity and is considered an important phenotypic trait influencing yield potential (12). Likewise, LAI is strongly related to canopy photosynthetic activity, biomass accumulation and final grain yield, with higher LAI generally supporting enhanced crop productivity (13). Depending on the severity, duration and timing of drought, maize yield losses may range from 30–90 %, with flowering and grain-filling stages being the most vulnerable (14). The mid-season drought reduced maize yield by approximately 39.3 %, while global yield reductions due to drought may reach 40 % (15). Furthermore, drought occurring during vegetative, flowering and grain-filling stages can reduce yield by approximately 25 %, 50 % and 21 %, respectively (16).

Moisture stress is one of the most critical abiotic constraints to maize production, affecting plant growth, photosynthetic efficiency, physiological processes and grain yield. Earlier studies have shown that the level of yield reduction is determined by the timing, duration and severity of water deficit, with the reproductive stage being the most sensitive to drought stress. Deficit irrigation is considered as an efficient approach for increasing irrigation productivity while reducing crop losses in regions with limited water supply. However, the effectiveness of deficit irrigation mostly depends on the crop growth stage at which moisture stress occurs.

Although several studies evaluated the effects of drought on maize, limited data available on the differential response of maize to moisture stress applied at different crop growth stages using irrigation water/cumulative pan evaporation (IW/CPE) based irrigation scheduling. Furthermore, the physiological mechanisms that maintain growth and productivity under moderate moisture stress compared to severe moisture stress remain understudied. As a result, the present study was intended to evaluate the effect of moisture stress applied at different crop growth stages on maize growth, physiological responses and yield, as well as to determine the most effective stage for deficit irrigation and whether moderate moisture stress may reduce irrigation water while maintaining crop productivity.

Materials and Methods

Study area and experimental design

A field experiment was conducted during the summer seasons of 2025 and 2026 at Field No. 37-F, Eastern Block Farm, Tamil Nadu Agricultural University, Coimbatore, India, located at 11.0168° N, 76.9558° E and 426.72 m mean sea level (MSL) (Fig. 1). The study was laid out in a randomised block design (RBD) with 10 irrigation treatments and 3 replications. The maize hybrid Advanta 751 PAC Elite was sown at a spacing of 60 × 25 cm with recommended dose

of fertiliser (RDF) of 250 : 75 : 75 kg ha⁻¹ of nitrogen (N) applied in three splits and the full dose of phosphorus (P) and potassium (K) applied as basal. All other agronomic practices were followed as per the crop production guide (CPG) (17) recommendations, except for irrigation management, which varied among treatments.

Weather data

During the summer 2025 season, weather conditions were characterised by daily maximum temperatures of 33.47 °C, minimum temperatures of 20.92 °C, relative humidity of 66.55 %, wind speed of 1.60 m s⁻¹, mean daily rainfall of 2.12 mm and daily evapotranspiration of 6.23 mm day⁻¹. During the summer 2026 season, 33.14 °C, minimum temperature of 19.55 °C, relative humidity of 62.57 %, wind speed of 1.65 m s⁻¹, mean daily rainfall of 0.91 mm and mean daily evapotranspiration of 6.48 mm day⁻¹.

Soil characteristics

The experimental field was classified as sandy clay loam with low to medium available N, medium P and high K content. Initial soil analysis indicated that the available N, P and K contents were 179.20, 19.88 and 686.00 kg ha⁻¹, respectively, during 2025 and 187.60, 21.60 and 616.00 kg ha⁻¹ during 2026, respectively. Soil bulk density varied from 1.07 to 1.27 g cm⁻³ across the study period.

Treatment application

Moisture stress treatments were applied through irrigation scheduling based on the IW/CPE approach. Uniform irrigation was applied at the time of sowing and life irrigation at 3 days after sowing (DAS) for all treatments; normal irrigation was maintained at an IW/CPE ratio of 0.75, whereas severe moisture stress was imposed at an IW/CPE ratio of 0.375 during specific crop growth stages (Table 1). The remaining irrigations were applied based on the treatment schedule (Table 2 and 3). The quantity of water applied at each irrigation event (50 mm) was measured using a Parshall flume. Effective rainfall between irrigation events was computed using daily crop evapotranspiration and expressed in milli meter (18). Progressive total evaporation, after accounting for effective rainfall, was maintained and irrigation was scheduled on attaining the pre-determined value of cumulative pan evaporation (CPE) (19). Irrigation is applied at ratio of irrigation water (IW) and CPE.

IW/CPE =

$$\frac{\text{Depth of water to be irrigated}}{\text{Cumulative pan evaporation for particular period}} \quad (\text{Eq. 1})$$

Irrigation scheduling was based on the IW/CPE approach, where IW represents the depth of irrigation water applied at each irrigation and CPE denotes the cumulative pan evaporation observed from USWB class A open pan evaporimeter between two successive irrigations.

Biometric observations

Growth and physiological parameters were recorded at 30, 60 and 90 DAS.

Plant height

Plant height was measured from the base of the plant to the tip of the topmost leaf from five randomly selected plants and average value was noted and expressed in cm.

Table 1. The treatment details of the study during summer 2025 and 2026

Treatments			IW/CPE ratio at different stages	
T ₁	-	Control	0.75 IW/CPE up to harvest	
T ₂	-	Early stress	0.75 IW/CPE up to 20 DAS	0.375 IW/CPE from 20 DAS to 50 DAS
T ₃	-	Mid stress	0.75 IW/CPE up to 50 DAS	0.375 IW/CPE from 50 DAS to 85 DAS
T ₄	-	Sustained deficit 1	0.75 IW/CPE up to 20 DAS	0.375 IW/CPE from 20 DAS to Harvest
T ₅	-	Sustained deficit 2	0.75 IW/CPE up to 50 DAS	0.375 IW/CPE from 50 DAS to Harvest
T ₆	-	Moderate stress 1	0.75 IW/CPE up to 70 DAS	0.375 IW/CPE from 70 DAS to Harvest
T ₇	-	Moderate stress 2	0.75 IW/CPE up to 85 DAS	0.375 IW/CPE from 85 DAS to Harvest
T ₈	-	Late stress 1	0.75 IW/CPE up to 20 DAS	No irrigation after 20 DAS
T ₉	-	Late stress 2	0.75 IW/CPE up to 50 DAS	No irrigation after 50 DAS
T ₁₀	-	Terminal stress	0.75 IW/CPE up to 85 DAS	No irrigation after 85 DAS

DAS: days after sowing; IW/CPE: irrigation water to cumulative pan evaporation ratio.

Table 2. Details of treatment imposition during summer 2025

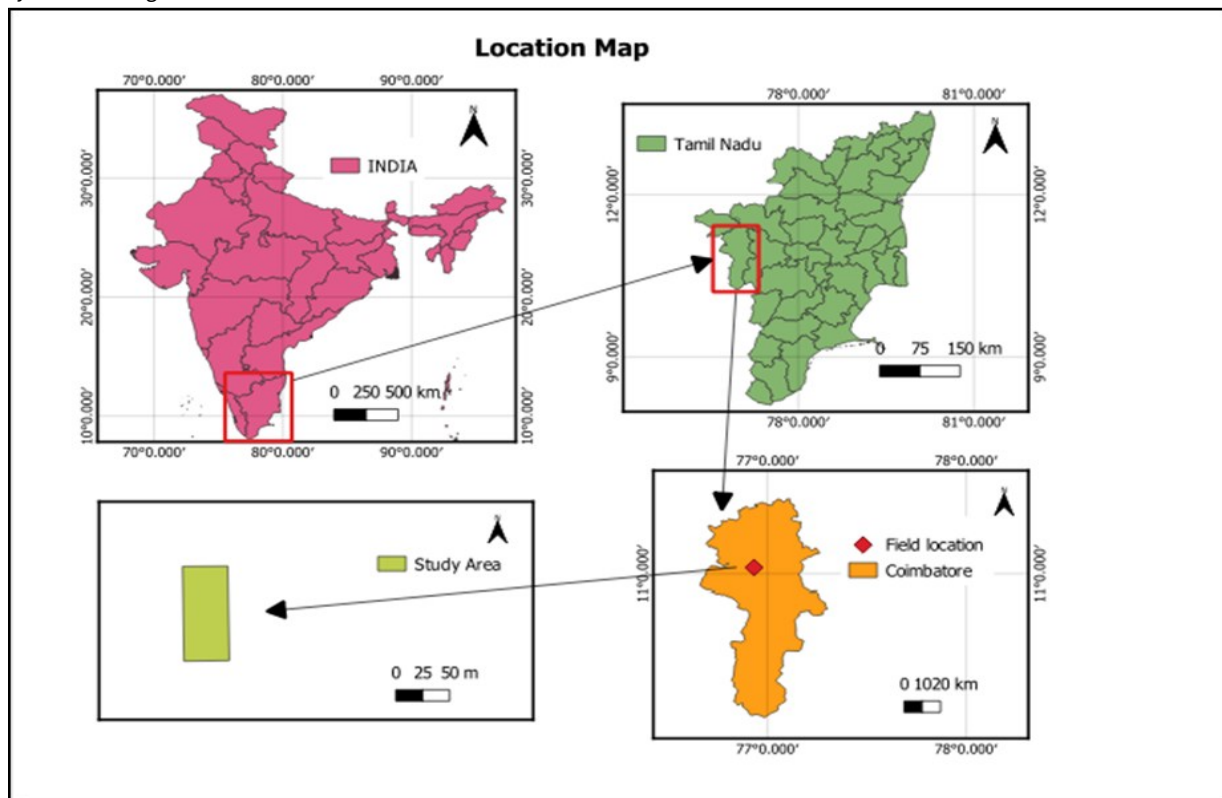
Treatments	Number of irrigations								
	1	2	3	4	5	6	7	8	9
T ₁	1 DAS	4 DAS	14 DAS	24 DAS	34 DAS	48 DAS	58 DAS	80 DAS	91 DAS
T ₂	1 DAS	4 DAS	14 DAS	34 DAS	51 DAS	61 DAS	84 DAS	95 DAS	-
T ₃	1 DAS	4 DAS	14 DAS	24 DAS	34 DAS	48 DAS	80 DAS	91 DAS	-
T ₄	1 DAS	4 DAS	14 DAS	34 DAS	59 DAS	92 DAS	-	-	-
T ₅	1 DAS	4 DAS	14 DAS	24 DAS	34 DAS	48 DAS	80 DAS	-	-
T ₆	1 DAS	4 DAS	14 DAS	24 DAS	34 DAS	48 DAS	58 DAS	91 DAS	-
T ₇	1 DAS	4 DAS	14 DAS	24 DAS	34 DAS	48 DAS	58 DAS	80 DAS	-
T ₈	1 DAS	4 DAS	14 DAS	-	-	-	-	-	-
T ₉	1 DAS	4 DAS	14 DAS	24 DAS	34 DAS	48 DAS	-	-	-
T ₁₀	1 DAS	4 DAS	14 DAS	24 DAS	34 DAS	48 DAS	58 DAS	80 DAS	-

DAS: days after sowing.

Table 3. Details of treatment imposition during summer 2026

Treatments	Number of irrigations									
	1	2	3	4	5	6	7	8	9	10
T ₁	1 DAS	4 DAS	19 DAS	34 DAS	45 DAS	55 DAS	69 DAS	79 DAS	89 DAS	101 DAS
T ₂	1 DAS	4 DAS	19 DAS	45 DAS	55 DAS	69 DAS	79 DAS	89 DAS	101 DAS	-
T ₃	1 DAS	4 DAS	19 DAS	34 DAS	45 DAS	69 DAS	85 DAS	94 DAS	-	-
T ₄	1 DAS	4 DAS	19 DAS	45 DAS	69 DAS	89 DAS	-	-	-	-
T ₅	1 DAS	4 DAS	19 DAS	34 DAS	45 DAS	69 DAS	89 DAS	-	-	-
T ₆	1 DAS	4 DAS	19 DAS	34 DAS	45 DAS	55 DAS	69 DAS	89 DAS	-	-
T ₇	1 DAS	4 DAS	19 DAS	34 DAS	45 DAS	55 DAS	69 DAS	79 DAS	101 DAS	-
T ₈	1 DAS	4 DAS	19 DAS	-	-	-	-	-	-	-
T ₉	1 DAS	4 DAS	19 DAS	34 DAS	45 DAS	-	-	-	-	-
T ₁₀	1 DAS	4 DAS	19 DAS	34 DAS	45 DAS	55 DAS	69 DAS	79 DAS	-	-

DAS: days after sowing.

**Fig. 1.** The geographic location of the experimental field during summer 2025 and summer 2026.

Source: Survey of India (SOI) base maps; figure prepared by the authors.

Leaf area index

The LAI was estimated using leaf length, maximum leaf width, a constant factor (0.75), number of leaves per plant and plant spacing (20).

LAI =
$$\frac{\text{Length} \times \text{width} \times \text{constant factor} \times \text{no. Of leaves per plant}}{\text{Spacing (cm}^2\text{)}} \quad (\text{Eq. 2})$$

Total chlorophyll

Total chlorophyll content was quantified using the acetone extraction method and measured absorbance at 645 and 663 nm using spectrophotometer and expressed in mg g⁻¹ of FW (21, 22).

Total chlorophyll =
$$(8.02 \times \text{OD } 663) + (20.2 \times \text{OD } 645) \times \frac{V}{1000 \times W} \quad (\text{Eq. 3})$$

Proline content

Proline content was estimated using sulphosalicylic acid, glacial acetic acid and toluene and its absorbance was measured at 520 nm using spectrophotometer using the below formula and expressed in mg g⁻¹ FW (23).

Proline (mg g⁻¹ FW) =
$$\frac{(\mu\text{g proline mL}^{-1} \times 4 \text{ mL toluene})}{(0.5 \text{ g sample}/2.5)} \times \frac{1}{1000} \quad (\text{Eq. 4})$$

Yield and yield parameters

Yield and yield parameters, including cob length (cm), cob girth (cm), cob weight (g), number of grains per cob, number of grains per row, test weight (g), grain yield (kg ha⁻¹) and stover yield (kg ha⁻¹), were recorded at harvest from five randomly tagged plants per plot and the average value was taken for analysis. Shelling percentage was calculated as the ratio of grain weight to total cob weight, while harvest index (HI) was determined as the ratio of economic yield to biological yield (24).

Harvest index (HI) =
$$\frac{\text{Economic yield (kg ha}^{-1}\text{)}}{\text{Biological yield (kg ha}^{-1}\text{)}} \quad (\text{Eq. 5})$$

A higher HI indicates greater partitioning of assimilates towards grain production, reflecting improved physiological efficiency and productivity, while lower HI indicates reduced biomass allocation to grains due to moisture stress or other unfavourable conditions.

Statistical analysis

The experimental data were subjected to analysis of variance (ANOVA) for randomized block design using R statistical software (version 4.5.3) and results were compared at the 5 % level of significance using least significance difference (LSD) test (25).

Results and Discussion

Plant height

Plant height was significantly affected by moisture stress treatments during both summer seasons (Table 4). Across all treatments, plant height increased progressively from 30–90 DAS, reflecting normal crop growth and development. During Summer 2025, the control (T1) recorded the highest plant height with values of 67.47, 190.63 and 193.67 cm, which remained statistically on par with moderate stress 2 (T7) with values of 65.40, 183.83 and 190.93 cm at 30, 60 and 90 DAS, respectively. In contrast, late stress 1 (T8) consistently recorded the lowest plant height, with values of 50.33, 167.80 and 172.00 cm at 30, 60 and 90 DAS, respectively. A similar trend was observed during summer 2026. The maximum plant height was recorded under the control (T1), with values of 74.40, 189.87 and 195.23 cm that were statistically comparable with moderate stress 2 (T7) of 69.10, 188.77 and 192.43 cm at 30, 60 and 90 DAS, respectively. Conversely, late stress 1 (T8) resulted in the lowest plant height throughout the season, recording 46.47, 144.53 and 151.33 cm at 30, 60 and 90 DAS, respectively.

Among the moisture stress treatments, the higher plant height observed under moderate stress 2 (T7) during both seasons indicated that moderate moisture stress did not substantially impair vegetative growth. Adequate soil moisture maintained cellular turgor, promoted cell division and stem elongation and sustained photosynthetic activity, thereby supporting continuous biomass accumulation. Moderate moisture stress has also been reported to enhance antioxidant defence and reduce oxidative damage, enabling plants to maintain normal physiological processes under water-deficit conditions (26). In contrast, severe moisture stress substantially reduced plant height by limiting cell expansion, reducing nutrient uptake and decreasing photosynthetic carbon assimilation, ultimately restricting vegetative growth. Similar reductions in plant height under prolonged water deficit have been reported in maize due to

Table 4. Effect of moisture stress treatments on plant height (cm) of maize during summer 2025 and summer 2026

Treatments			Summer (2025)			Summer (2026)		
			30 DAS	60 DAS	90 DAS	30 DAS	60 DAS	90 DAS
T ₁	-	Control	67.47	190.63	193.67	74.40	189.87	195.23
T ₂	-	Early stress	58.27	174.67	178.40	57.07	164.23	168.93
T ₃	-	Mid stress	58.73	175.47	182.70	58.87	177.50	179.20
T ₄	-	Sustained deficit 1	52.33	168.30	173.90	47.67	146.60	151.50
T ₅	-	Sustained deficit 2	55.40	172.33	175.57	55.70	162.27	167.33
T ₆	-	Moderate stress 1	59.83	179.00	186.37	59.60	182.70	186.33
T ₇	-	Moderate stress 2	65.40	183.83	190.93	69.10	188.77	192.43
T ₈	-	Late stress 1	50.33	167.80	172.00	46.47	144.53	151.33
T ₉	-	Late stress 2	53.57	171.47	174.87	53.87	151.13	156.50
T ₁₀	-	Terminal stress	62.60	179.67	188.03	62.67	183.13	190.23
S.Ed			3.80	5.58	4.07	4.95	6.96	5.16
CD (<i>p</i> = 0.05)			7.98	11.73	8.54	10.39	14.61	10.85

DAS: days after sowing.

impaired vegetative growth and reduced physiological activity (27, 28).

Leaf area index

The LAI was significantly affected by moisture stress treatments during both summer seasons (Fig. 2 A and B). In summer 2025, the control (T1) recorded the highest LAI (3.29), followed by moderate stress 2 (T7) (2.90) at 30 DAS, whereas the control (T1) at the remaining stages (6.13 and 5.75) was on par with moderate stress 2 (T7) (5.65) and (5.60) at 60 and 90 DAS, respectively. In contrast, late stress 1 (T8) recorded the lowest LAI values of 1.74, 3.94 and 3.01 at 30, 60 and 90 DAS, respectively. During summer 2026 the highest LAI was recorded under control (T1) with 3.61, 6.47 and 6.01, which remained statistically comparable with moderate stress 2 (T7) 3.35, 6.18 and 5.80 at 30, 60 and 90 DAS, respectively. Conversely, late stress 1 (T8) consistently recorded the lowest LAI values of 2.26, 4.25 and 4.15 at 30, 60 and 90 DAS, respectively.

The higher LAI observed under moderate stress 2 (T7) indicates that adequate soil moisture-maintained leaf expansion and canopy development, thereby improving radiation interception and sustaining photosynthetic activity. Maintenance of canopy structure under moderate moisture stress enhanced assimilate production, which contributed to continued crop growth and productivity. Maintaining an optimum leaf area index improves radiation use efficiency, evapotranspiration efficiency and grain yield under deficit irrigation (29). Similarly, maintenance of canopy characteristics, particularly LAI, is essential for sustaining photosynthetic efficiency and crop productivity under water-limited conditions and a positive relationship has been reported between LAI and maize productivity (30, 31). In contrast, severe moisture

stress markedly reduced LAI by restricting cell expansion, accelerating leaf senescence and decreasing radiation interception, which consequently reduced photosynthetic carbon assimilation and biomass production. Similar findings have been reported, where severe water stress inhibited leaf expansion and accelerated leaf senescence, resulting in reduced LAI, biomass accumulation and grain yield in maize (32). Likewise, reduced canopy development under drought stress has been associated with lower LAI, decreased biomass production and reduced maize productivity (33).

Chlorophyll content

Chlorophyll content serves as a reliable indicator of the photosynthetic efficiency of plants under stress conditions. Moisture stress treatments significantly influenced chlorophyll pigments and carotenoid content at all growth stages during both summer seasons (Fig. 3 A and B). During summer 2025, the control (T1) recorded the highest values of 2.57 and 2.02 mg g⁻¹ FW, which were statistically on par with moderate stress 2 (T7), which recorded 2.46, 1.88 mg g⁻¹ FW of total chlorophyll at 30 and 60 DAS, respectively, whereas at 90 DAS the control (T1) recorded 1.86 mg g⁻¹ FW, followed by 1.64 mg g⁻¹ FW of total chlorophyll in moderate stress 2 (T7). In contrast, late stress 1 (T8) recorded the lowest values of 1.42, 0.99 and 0.75 mg g⁻¹ FW total chlorophyll at 30, 60 and 90 DAS, respectively, during summer 2025.

During summer 2026, the control (T1) recorded the highest values of 2.50, 1.82 and 1.65 mg g⁻¹ FW was on par with moderate stress 2 (T7) 2.40, 1.76 and 1.58 mg g⁻¹ FW of total chlorophyll at 30, 60 and 90 DAS respectively, whereas late stress 1 (T8) recorded the lowest pigment concentrations of 1.35, 0.91 and 0.61 mg g⁻¹ FW of total chlorophyll at 30, 60 and 90 DAS respectively.

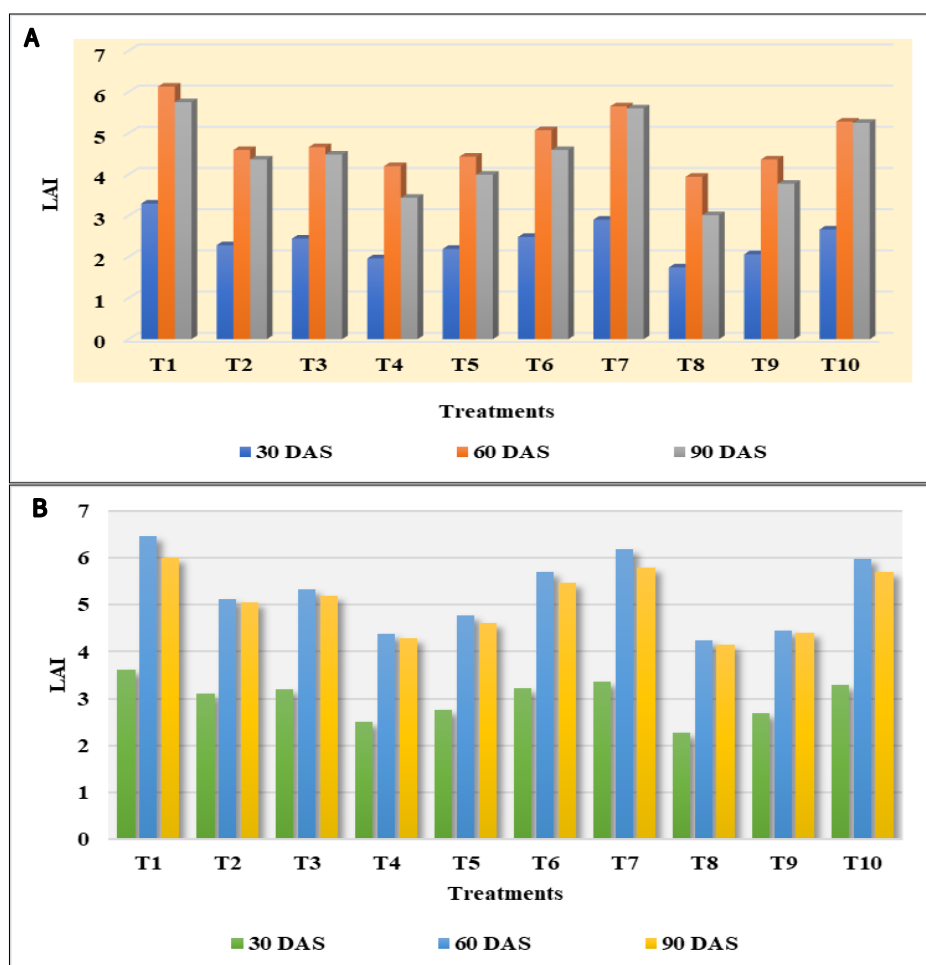


Fig. 2. Effect of moisture stress treatments on leaf area index (LAI) of maize. A: During summer 2025; B: During summer 2026

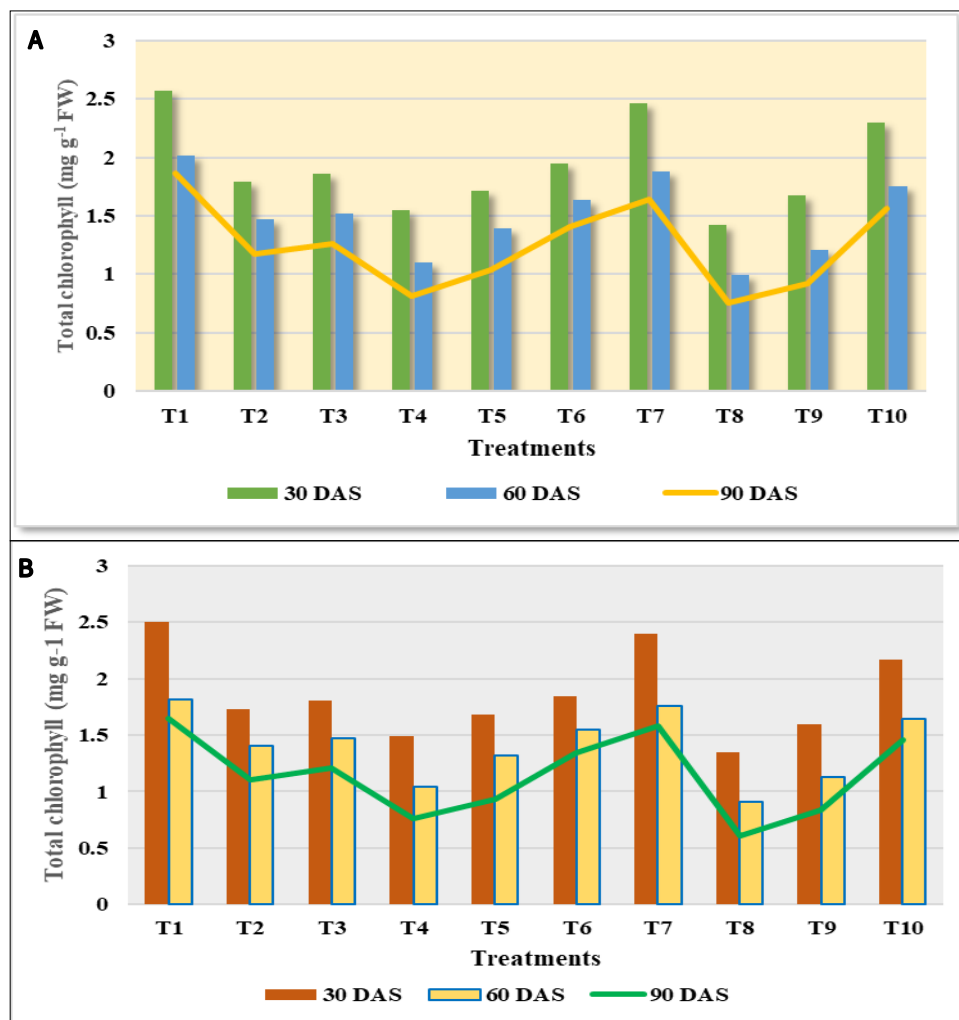


Fig. 3. Effect of moisture stress treatments on total chlorophyll (mg g^{-1} FW) of maize. A: During summer 2025; B: During summer 2026.

The relatively higher chlorophyll content observed under moderate stress 2 (T7) indicates that moderate moisture stress largely sustained chlorophyll biosynthesis and chloroplast degradation, thereby maintaining photosynthetic efficiency. Sustained chlorophyll concentration under T7 enhanced light harvesting and carbon assimilation, contributing to improved crop growth and productivity. Similar adaptive responses in maize under moderate water stress, including maintenance of photosynthetic pigments and recover crop from stress by irrigation (34). Enhanced osmotic regulation and antioxidant defence have also been shown to reduce oxidative damage and protect the photosynthetic machinery under drought conditions (35). In contrast, severe moisture stress markedly reduced chlorophyll content by restricting nutrient uptake and accelerating chlorophyll degradation through excessive accumulation of ROS. Oxidative damage to chloroplast membranes impaired photosynthetic carbon assimilation, thereby reducing plant growth and biomass production. Comparable reductions in chlorophyll content and photosynthetic efficiency under drought stress have been reported in maize during the reproductive stage (36), while physiological and molecular studies have demonstrated that oxidative stress accelerates chlorophyll degradation and disrupts photosynthetic processes under adverse environmental conditions (37, 38).

Proline content

Proline content was significantly influenced by moisture stress treatments during both seasons and increased with crop stage and stress intensity was represented using violin plot (Fig. 4). During

summer 2025, the highest proline accumulation was recorded under late stress 1 (T8), with values of 0.60, 2.13 and 3.25 mg g^{-1} FW at 30, 60 and 90 DAS, respectively. In contrast, the control (T1) recorded the lowest proline contents of 0.24, 0.38 and 0.48 mg g^{-1} FW and remained statistically comparable with the moderate stress 2 (T7) with relatively low proline concentrations of 0.28, 0.46 and 0.61 mg g^{-1} FW at 30, 60 and 90 DAS, respectively.

A similar trend was observed during summer 2026. The highest proline accumulation was again recorded under late stress 1 (T8), with values of 0.69, 2.32 and 3.49 mg g^{-1} FW at 30, 60 and 90 DAS, respectively. Conversely, the control (T1) recorded the lowest proline contents of 0.25, 0.39 and 0.52 mg g^{-1} FW, which were statistically on par with moderate stress 2 (T7), which recorded 0.27, 0.52 and 0.69 mg g^{-1} FW at 30, 60 and 90 DAS, respectively.

The relatively low proline accumulation observed under moderate stress 2 (T7) indicates that plants experienced only mild physiological stress and maintained favourable cellular water status, thereby minimising the requirement for osmotic adjustment. In contrast, severe moisture stress significantly increased proline accumulation as an adaptive response to cellular dehydration. Proline acts as a compatible osmolyte by maintaining osmotic balance, stabilising cellular membranes and proteins, protecting the photosynthetic apparatus and scavenging ROS, thereby enhancing stress tolerance under drought conditions. Regulated deficit irrigation has been reported to reduce physiological stress and proline accumulation while

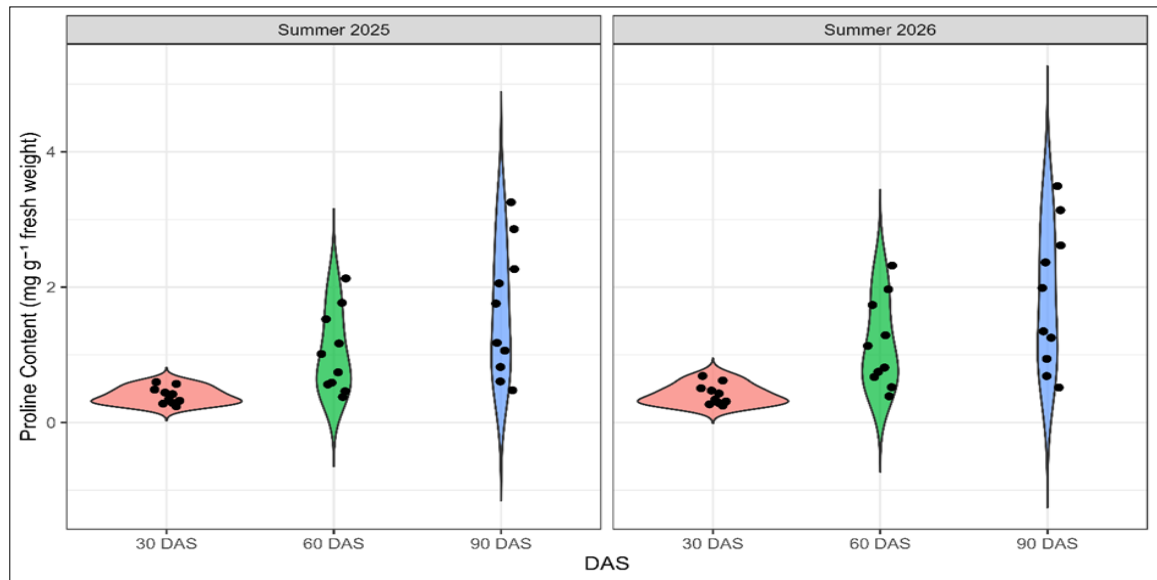


Fig. 4. Effect of moisture stress treatments on proline content (mg g⁻¹ FW) of maize during summer 2025 and summer 2026.

improving water use efficiency in maize (39). Similarly, enhanced antioxidant defence mechanism has mitigated oxidative damage and improve stress tolerance, whereas progressive proline accumulation with increasing moisture stress intensity serves as an important mechanism for osmotic adjustment and cellular protection (40,41).

Yield attributes

Yield attributes were significantly influenced by moisture stress treatments during both seasons (Table 5 and 6). During summer 2025, the control (T1) recorded the highest cob length (18.14 cm), cob girth (15.40 cm), grains per row (18.68), grains per cob (718.04), cob weight (150.25 g cob⁻¹), test weight (33.82 g) and shelling percentage (81.52 %); they remained statistically comparable with moderate stress 2 (T7) recording cob length

(17.68 cm), cob girth (15.10 cm), grains per row (18.32), grains per cob (668.34), cob weight (147.48 g cob⁻¹), test weight (33.15 g) and shelling percentage (79.60 %). In contrast, late stress 1 (T8) recorded the lowest values for all yield attributes, with cob length (14.41 cm), cob girth (11.17 cm), grains per row (14.73), grains per cob (334.49), cob weight (106.79 g cob⁻¹), test weight (27.87 g) and shelling percentage (68.41 %).

The same trend was observed during summer 2026. The highest values were recorded under the control (T1) with cob length (17.42 cm), cob girth (14.82 cm), grains per row (18.23), grains per cob (682.56), cob weight (147.45 g cob⁻¹), test weight (32.81 g) and shelling percentage (81.96 %) values, which were comparable with moderate stress 2 (T7) recording cob length (16.87 cm), cob girth (14.74 cm), grains per row (17.84),

Table 5. Effect of moisture stress treatments on yield parameters of maize during summer 2025

			Summer (2025)						
Treatments			Cob length (cm)	Cob grith (cm)	No. of grains per row	No. of grains cob ⁻¹	Cob weight (g cob ⁻¹)	Test weight (g)	Shelling (%)
T ₁	-	Control	18.14	15.40	18.68	718.04	150.25	33.82	81.52
T ₂	-	Early stress	16.28	14.27	17.01	540.39	130.16	31.64	71.64
T ₃	-	Mid stress	16.62	14.63	17.25	587.55	139.34	31.87	69.96
T ₄	-	Sustained deficit 1	14.73	13.50	15.26	438.91	110.61	29.71	71.17
T ₅	-	Sustained deficit 2	15.85	14.03	16.50	522.36	128.27	31.05	70.40
T ₆	-	Moderate stress 1	17.16	15.00	17.67	599.98	140.12	32.32	73.60
T ₇	-	Moderate stress 2	17.68	15.37	18.32	668.34	147.48	33.15	79.60
T ₈	-	Late stress 1	14.41	11.17	14.73	334.49	106.79	27.87	68.41
T ₉	-	Late stress 2	15.54	13.93	15.74	536.01	115.56	30.34	74.65
T ₁₀	-	Terminal stress	17.32	15.17	18.00	623.38	145.63	32.82	75.30
S.Ed			0.98	1.00	0.88	34.96	7.21	1.54	3.60
CD (p = 0.05)			2.06	2.09	1.85	73.44	15.14	3.24	7.56

Table 6. Effect of moisture stress treatments on yield parameters of maize during summer 2026

			Summer (2026)						
Treatments			Cob length (cm)	Cob grith (cm)	No. of grains per row	No. of grains cob ⁻¹	Cob weight (g cob ⁻¹)	Test weight (g)	Shelling (%)
T ₁	-	Control	17.42	14.82	18.23	682.56	147.45	32.81	81.96
T ₂	-	Early stress	14.56	13.21	15.92	448.54	123.96	30.73	76.34
T ₃	-	Mid stress	15.13	13.83	16.45	440.64	134.35	31.25	70.49
T ₄	-	Sustained deficit 1	12.44	12.28	14.35	345.86	102.45	28.19	67.49
T ₅	-	Sustained deficit 2	14.31	12.89	15.57	361.03	117.63	30.58	73.07
T ₆	-	Moderate stress 1	15.6	14.27	16.86	507.01	137.16	31.47	70.18
T ₇	-	Moderate stress 2	16.87	14.74	17.84	621.79	145.20	32.56	75.43
T ₈	-	Late stress 1	12.02	12.02	13.74	284.06	100.88	25.15	65.16
T ₉	-	Late stress 2	13.58	12.65	14.81	369.46	107.43	29.34	70.51
T ₁₀	-	Terminal stress	16.29	14.46	17.38	597.22	142.42	31.92	72.79
S.Ed			0.94	0.73	1.06	25.58	7.45	1.73	4.04
CD (p = 0.05)			1.97	1.53	2.24	53.74	15.64	3.64	8.48

grains per cob (621.79), cob weight (147.48 g cob⁻¹), test weight (32.56 g) and shelling percentage (75.43 %). Conversely, late stress 1 (T8) recorded the lowest values of cob length (12.02 cm), cob girth (12.02 cm), grains per row (13.74), grains per cob (284.06), cob weight (100.88 g cob⁻¹), test weight (25.15 g) and shelling percentage (65.16 %).

The superior yield attributes observed under moderate stress 2 (T7) indicate that moderate moisture stress did not substantially reduce reproductive development. Adequate soil moisture during the critical reproductive stage maintained successful pollination and fertilisation, minimised the anthesis silking interval and promoted efficient kernel set and grain filling. Sustained photosynthetic activity and efficient assimilate partitioning from source leaves to developing cobs contributed to higher cob length, cob girth, grains per row, grains per cob and cob weight, which remained comparable with the control (T1). Moderate stress has been reported to improve assimilate translocation and grain filling by enhancing the remobilisation of photosynthates to developing grains (42). In contrast, severe moisture stress significantly reduced reproductive performance by prolonging the anthesis silking interval, limiting pollination success, reducing assimilate production and restricting grain filling, thereby lowering yield attributes. Although remobilisation of stored stem carbohydrates partially supported grain development, it was inadequate to compensate for the decline in photosynthesis under severe stress conditions, as reflected by the reduced canopy development and chlorophyll content were observed (30). Similarly, increased plant growth and adequate moisture availability have been reported to enhance assimilate translocation, reproductive development and water productivity in maize, whereas severe moisture stress reduced kernel development and yield components (43).

Grain yield and stover yield

Grain yield was significantly influenced by moisture stress treatments during both seasons. The control (T1) recorded the highest grain yield of 8163 and 8057 kg ha⁻¹ and remained statistically comparable with moderate stress 2 (T7), which recorded 7794 and 7283 kg ha⁻¹ during summer 2025 and summer 2026, respectively. In contrast, late stress (T8) recorded the lowest grain yield of 4872 and 4352 kg ha⁻¹ during summer 2025 and summer 2026, respectively.

During summer 2025, the highest stover yield was recorded under the control (T1) with 12345 kg ha⁻¹, which was statistically on par with 11871 and 11266 kg ha⁻¹ in moderate stress 2 (T7) and terminal stress (T10), respectively. During summer 2026, the control (T1) recorded the highest stover yield of 12162 kg ha⁻¹, which remained on par with moderate stress 2 (T7) of 11465 kg ha⁻¹.

Conversely, late stress (T8) recorded the lowest stover yield of 8130 and 7926 kg ha⁻¹ during summer 2025 and summer 2026, respectively. Harvest index was statistically non significant among stress treatments during both seasons (Table 7).

The higher grain yield recorded under moderate stress 2 (T7) was primarily attributed to enhanced vegetative growth, improved leaf surface area and efficient partitioning of photo assimilate towards reproductive sinks, which ensured an adequate carbohydrate supply for grain development. Moderate moisture stress likely enhanced nutrient uptake and utilisation efficiency while maintaining antioxidant activity, thereby protecting reproductive tissues and sustaining grain filling under water limited conditions (44, 45). In contrast, severe moisture stress drastically reduced grain yield by impaired reproductive processes, including pollen sterility, ovule abortion, poor fertilisation and restricted grain filling (15, 46). A reduction in grain filling rate and duration under prolonged drought further decreased grain weight and yield (47). Similar reductions in maize productivity under deficit irrigation have also been reported under severe moisture stress (48). The superior performance of T7 suggests that maintaining adequate irrigation until 85 DAS protected the crop during the critical flowering and grain-filling stages, thereby sustaining photosynthesis, assimilate partitioning and reproductive development while reducing irrigation water use compared with the well-watered control (T1).

Conclusion

The present study evaluated that the timing and intensity of moisture stress significantly influenced the growth, physiological traits, yield attributes and productivity of maize. The findings revealed that moderate stress 2 (T7) was the most effective irrigation strategy among the stress treatments, maintaining growth, physiological performance and yield levels comparable to the well-watered control (T1). The ability of moderate stress 2 (T7) to maintain leaf area development, retain chlorophyll pigments and maintain lower proline accumulation contributed to increased assimilate production, reproductive development and grain filling. The results suggest that maintaining adequate moisture until 85 days after sowing (DAS), followed by moderate deficit irrigation, is an effective irrigation strategy for improving water use efficiency while sustaining maize productivity under water deficit conditions. This irrigation schedule can therefore be recommended for efficient moisture stress management in maize cultivation under similar agro climatic conditions. Additionally, future research should focus on validating this irrigation strategy across different maize hybrids, soil types and climatic regions and integrating physiological measurements with

Table 7. Effect of moisture stress treatments on grain and stover yield (kg ha⁻¹) of maize

Treatments		Grain yield		Stover yield		HI	
		Summer (2025)	Summer (2026)	Summer (2025)	Summer (2026)	Summer (2025)	Summer (2026)
T ₁	- Control	8163	8057	12345	12162	0.47	0.49
T ₂	- Early stress	6199	6270	9868	9916	0.44	0.46
T ₃	- Mid stress	6434	6310	10251	10153	0.43	0.44
T ₄	- Sustained deficit 1	5226	4610	8662	8472	0.43	0.39
T ₅	- Sustained deficit 2	6001	5734	9547	9341	0.44	0.44
T ₆	- Moderate stress 1	6850	6406	10785	10517	0.45	0.44
T ₇	- Moderate stress 2	7794	7283	11871	11465	0.46	0.46
T ₈	- Late stress 1	4872	4352	8130	7926	0.42	0.40
T ₉	- Late stress 2	5746	5106	9024	8768	0.45	0.40
T ₁₀	- Terminal stress	7244	6923	11266	10974	0.46	0.46
S.Ed		304.13	442.78	542.78	498.76	0.04	0.05
CD (<i>p</i> = 0.05)		638.96	930.24	1140.35	1047.86	NS	NS

HI: harvest index.

drone-based remote sensing and crop simulation models to develop precision irrigation strategies for sustainable maize production under changing climate conditions.

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Authors' contributions

SG conceived the idea and wrote the manuscript. VM and RJ revised and reviewed the manuscript. KT, PB and RR reviewed and finalised the manuscript. All authors have read and approved the final manuscript.

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During the preparation of this work the authors used Quillbot to improve language and for grammar correction. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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