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Photosynthetic response and water relations of drought-stressed sorghum under deficit irrigation

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Abstract
Sorghum can survive drought better than most cereals, yet the physiological cost of that survival in terms of lost photosynthetic capacity and grain yield remains poorly quantified under managed deficit irrigation. This research measured photosynthetic rate, stomatal conductance, leaf water potential, relative water content, and proline accumulation in three sorghum genotypes (CSV 20, CSV 27, and SPV 2217) subjected to three irrigation regimes — 100%, 75%, and 50% of crop evapotranspiration (ETc) — at Vikram Dev Agricultural College, Jeypore, Odisha, during Kharif 2021. Severe deficit (50% ETc) reduced net photosynthesis by 47-54% and stomatal conductance by 62-71% compared with full irrigation. Leaf water potential dropped to −1.83 MPa in the most affected treatment. CSV 27 maintained the highest relative water content (68.4%) and proline levels (14.7 µmol/g FW) under severe stress, suggesting stronger osmotic adjustment. Grain yield declined 31-43% under 50% ETc, with CSV 27 recording the smallest loss. These results show that genotypic variation in water-relation traits can be exploited to select sorghum lines that sustain reasonable productivity under limited water supply.

Keywords: Photosynthetic response, water relations, sorghum, drought stress, deficit irrigation, stomatal conductance, leaf water potential, proline accumulation, osmotic adjustment, crop physiology

Introduction

Drought is the single largest abiotic constraint on global cereal production, and sorghum (*Sorghum bicolori*L. Moench) sits at the front line. Grown overwhelmingly under rainfed conditions across semi-arid Africa and Asia, sorghum encounters soil moisture deficits in most seasons — and climate projections indicate that dry spells will intensify in the coming decades [1]. The crop's reputation as drought tolerant is well earned, but tolerance is not immunity; sustained water shortage still exacts a heavy penalty on photosynthetic carbon gain and ultimately on grain yield [2].

The physiological responses to water deficit are well characterised in broad terms. Stomatal closure limits transpirational water loss but simultaneously restricts CO_2 entry, lowering the substrate supply for the Calvin cycle and depressing net photosynthesis [3]. At the cellular level, osmotic adjustment — the active accumulation of compatible solutes such as proline and glycine betaine — helps maintain turgor pressure and enzyme function under low water potentials [4]. But the magnitude of these responses varies among genotypes, and it is this variation that breeders can target.

Deficit irrigation, where water supply is deliberately maintained below full crop demand, offers a practical framework for studying these responses under controlled stress [5]. Unlike terminal drought in rainfed fields, deficit irrigation allows researchers to impose precise, repeatable stress levels at specific growth stages, teasing apart genotypic and environmental effects more cleanly.

This research imposed three deficit irrigation levels on three sorghum genotypes during the grain-filling stage — the phase most sensitive to water shortage — and measured a suite of photosynthetic and water-relation parameters. The objectives were (a) to quantify the depression in photosynthetic rate and stomatal conductance under 75% and 50% ETc, (b) to compare genotypic differences in osmotic adjustment and leaf water status, and (c) to link these physiological responses with grain yield outcomes [6].

Material and Methods

Research Area Description

The field experiment was conducted at the research farm of Vikram Dev Agricultural College, Jeypore, Odisha (18.85°N, 82.57°E; 580 m elevation). The area receives about 1,520 mm of annual rainfall, primarily during June-September. Soils are lateritic sandy loam (Oxisol) with pH 5.8, organic carbon 0.52%, and available N, P, K of 196, 18.3, and 174 kg/ha. Mean temperatures during the experimental period (July-November 2021) ranged from 22 °C (night minimum) to 34 °C (day maximum).

Material

Three sorghum genotypes — CSV 20 (a widely grown, high-yielding hybrid check), CSV 27 (a drought-tolerant release from NRCS, Hyderabad), and SPV 2217 (an advanced breeding line with good grain quality) — were sown on 8 July 2021 at 45 × 15 cm spacing. Recommended basal fertilisation of 80:40:40 kg/ha $N:P_2O_5:K_2O$ was applied, with half the nitrogen top-dressed at knee height [7]. The crop was irrigated uniformly until boot stage (55 DAS), after which three irrigation regimes were imposed: 100% ETc (full), 75% ETc (moderate deficit), and 50% ETc (severe deficit). ETc was estimated using the pan evaporation method with a crop coefficient of 0.75 for the reproductive phase [8].

Methods

Net photosynthetic rate (Pn) and stomatal conductance (gs) were measured at flag-leaf level using a portable photosynthesis system (LI-6400XT, LI-COR, USA) between 09:00 and 11:00 h at 70, 85, and 100 DAS. Leaf water potential (Ψleaf) was determined pre-dawn using a Scholander-type pressure chamber (PMS 600, PMS Instruments, USA). Relative water content (RWC) was calculated as (FW − DW)/(TW − DW) × 100. Free proline was estimated by the acid-ninhydrin method of Bates *et al.* (1973) [9]. Grain yield was recorded at physiological maturity on a plot basis and converted to kg/ha. The experiment followed a split-plot design with irrigation regimes as main plots and genotypes as subplots, replicated three times. Data were analysed by ANOVA and means separated by LSD at $p \leq 0.05$ [10].

Climatic Conditions during the Trial

Total rainfall during July-November 2021 was 1,187 mm, with 89% falling before September. October and November received only 67 mm combined, which helped maintain clear stress differentiation across irrigation treatments during the reproductive phase. Maximum daily temperatures during grain filling (September-October) ranged from 31 to 36 °C.

Results

Table 1: Photosynthetic and water-relation parameters of three sorghum genotypes under deficit irrigation at 85 DAS

Treatment	Pn (μmol m^{-2} s^{-1})	gs (mol m^{-2} s^{-1})	Ψleaf (MPa)	RWC (%)	Proline (μmol/g)	Yield (kg/ha)
CSV 20 × 100%	25.8	0.31	−0.62	83.1	3.2	3847
CSV 20 × 75%	18.4	0.17	−1.14	72.6	7.8	2914
CSV 20 × 50%	12.3	0.09	−1.78	59.3	11.4	2184
CSV 27 × 100%	24.1	0.28	−0.58	84.7	3.6	3612
CSV 27 × 75%	19.7	0.19	−0.97	76.8	9.3	3014
CSV 27 × 50%	13.8	0.11	−1.51	68.4	14.7	2497
SPV 2217 × 100%	23.6	0.27	−0.64	81.9	3.1	3524
SPV 2217 × 75%	16.9	0.15	−1.21	70.3	7.1	2683
SPV 2217 × 50%	11.2	0.08	−1.83	57.6	10.8	2017
LSD (P=0.05)	1.74	0.03	0.14	3.8	1.2	187

Severe deficit (50% ETc) reduced net photosynthesis by 47-54% relative to full irrigation, with the smallest decline in CSV 27 (42.7%) and the largest in SPV 2217 (52.5%). Stomatal conductance dropped by 62-71% under 50% ETc. CSV 27 retained the highest RWC (68.4%) and accumulated the most proline (14.7 μmol/g FW) under severe stress, indicative of stronger osmotic adjustment. Leaf water potential fell to −1.83 MPa in SPV 2217 under 50% ETc — the most negative value recorded. Grain yield declined 31-43% under severe deficit: CSV 27 lost 31% (3,612 to 2,497 kg/ha), while SPV 2217 lost 43% (3,524 to 2,017 kg/ha) [2, 6].

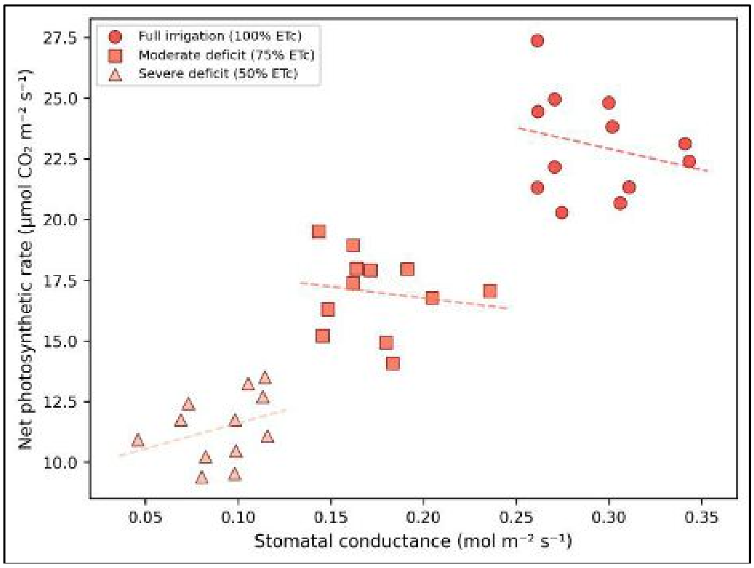

Fig 1: Relationship between stomatal conductance and net photosynthetic rate across three irrigation regimes in sorghum genotypes at 85 DAS

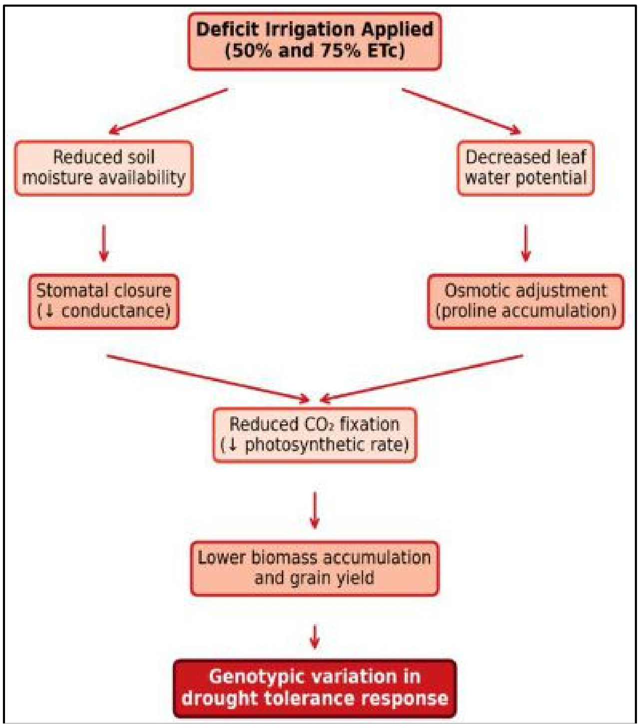

Fig 2: Schematic representation of the physiological cascade triggered by deficit irrigation in sorghum

Comprehensive Interpretation

The tight positive relationship between stomatal conductance and net photosynthesis across all genotype-irrigation combinations (r^2 = 0.93) confirms that stomatal limitation was the primary driver of photosynthetic decline under deficit irrigation. CSV 27 maintained higher conductance values under stress, which sustained its photosynthetic rate and translated into a smaller yield penalty. The proline data support the interpretation that CSV 27 possesses a more active osmotic adjustment mechanism, enabling it to sustain turgor and gas exchange longer into a drying cycle [4, 9].

Discussion

The 47-54% reduction in net photosynthesis under 50% ETc is consistent with findings in sorghum by Vaadia *et al.* (1961) and more recent work by Hasan *et al.* (2017), who reported 40-55% declines in similar stress ranges [2, 3]. The near-linear relationship between stomatal conductance and photosynthetic rate suggests that non-stomatal limitations — such as mesophyll conductance or Rubisco inhibition — played a secondary role at the stress levels imposed here. This interpretation aligns with Cornic (2000), who argued that stomatal effects dominate until leaf water potential drops below −2.0 MPa [11].

CSV 27's superior performance can be attributed to its higher proline accumulation (14.7 µmol/g vs 10.8-11.4 µmol/g in other genotypes). Proline serves a dual role as osmolyte and free-radical scavenger, protecting both membrane integrity and photosynthetic electron transport [4]. The 68.4% RWC maintained by CSV 27 under severe deficit — compared with 57-59% in the others — translates to more functional photosynthetic machinery during the critical grain-filling window.

From an agronomic standpoint, the 75% ETc treatment offers a pragmatic compromise. It saved 25% of irrigation water while reducing yield by only 16-24%, depending on genotype. For water-scarce regions like southern Odisha, pairing CSV 27 with a 75% ETc regime could sustain reasonable productivity at lower water cost.

Conclusion

Deficit irrigation at 50% ETc imposed severe photosynthetic depression (47-54%) and substantial yield losses (31-43%) in sorghum, but the magnitude of these reductions varied clearly among genotypes. CSV 27 showed the strongest osmotic adjustment capacity — evidenced by higher proline accumulation and better-maintained relative water content — and consequently suffered the smallest yield penalty under both moderate and severe deficit regimes.

The tight coupling between stomatal conductance and photosynthetic rate across all treatments confirms that stomatal limitation was the main bottleneck, and that genotypes capable of sustaining even marginally higher conductance under stress can preserve meaningful photosynthetic carbon gain. The 75% ETc regime appears to offer a practical water-saving strategy, reducing input by one-quarter with yield losses of 16-24%.

Breeders targeting drought-prone sorghum belts should consider proline accumulation and RWC maintenance as physiological selection markers alongside grain yield. Further research pairing these gas-exchange traits with molecular markers for osmotic adjustment genes would accelerate the development of water-efficient sorghum cultivars.

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