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RESEARCH ARTICLE

Assessment of foliar-applied stress regulators to sustain the growth and yield of wheat varieties under various irrigation levels

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Abstract

This study was conducted to evaluate the interactive effects of irrigation levels, wheat varieties and foliar application of stress regulators on growth, yield and economic returns of wheat. A field experiment was laid out in a split-split plot design during the Rabi 2021-22 season at JNKVV, Jabalpur (M.P.) comprising three irrigation levels (one irrigation at CRI, two irrigations at CRI and flowering and three irrigations at CRI, flowering and milking stages), two wheat varieties (JW 3288 and JW 3382) and five foliar applications (control, 1 % potassium chloride, 2 % potassium chloride, 0.1 % ascorbic acid and 0.2 % ascorbic acid) applied at tillering and flowering stages. Results revealed that three irrigations at CRI, flowering and milking stages significantly enhanced plant height, tiller number, leaf area index, dry matter accumulation, grain yield and straw yield compared to reduced irrigation levels. Among varieties, JW 3288 consistently outperformed JW 3382, indicating its greater adaptability and moisture stress tolerance. Foliar application of 2 % KCl markedly improved growth, yield attributes and yield by enhancing osmotic regulation, assimilate partitioning and leaf water status under limited moisture. Ascorbic acid applications provided moderate benefits by stabilizing chlorophyll and mitigating oxidative stress effects during water-deficient periods. The highest productivity and profitability were achieved under the combination of three irrigations, JW 3288 variety and 2 % KCl foliar spray, demonstrating significant interaction effects among irrigation, variety and foliar stress regulation practices. These results highlight the potential of integrated agronomic strategies for enhancing wheat resilience and yield in wheat-growing regions.

Keywords: foliar application; irrigation levels; potassium chloride; sustainable production; wheat varieties

Introduction

The exponential increase in the world's population is expected to increase the demand for wheat in human nutrition over the next two to three decades (1). In addition to its importance in terms of acreage, wheat is one of India's most versatile crops, adapting to a variety of agroclimatic conditions and crop-growing scenarios (2). With over 13 % protein, which is far higher than that of other main cereals, wheat is the most important source of vegetable protein in human diets worldwide. It is also a substantial source of calories and carbohydrates with almost no fat (3). Wheat is essential to the manufacturing of bread, cakes, biscuits, noodles, chapattis and other foods in India, where it supports national food security (4). Due to increasing demographic pressure, it is vital to continuously increase the yield of food crops, particularly wheat, to ensure food security (5). After rice and maize, it is the most cultivated cereal worldwide and commonly found in the diets of 35 % of the world's population (6). With a total area of 220.41 M ha and a productivity of 3.63 tons/ha in 2023, wheat is grown worldwide under a variety of agroclimatic conditions. India is currently the world's second-largest wheat producer, having made enormous progress in the last forty years. During the rabi season, it is cultivated in India in a subtropical climate on 31.82 million hectares, yielding 112.74 million tons and 3543 kg/ha of productivity. Due to its special gluten properties, it is essential for processed meals and its demand is rising because of global industrialization and a trend toward Western eating patterns.

Irrigation is a valuable and limited input that is necessary for maintaining turgidity, nutrient absorption and plant metabolism to maximize crop yield (7). To ensure the adequate amount and duration of water application, irrigation planning is a crucial component of water management (8). In arid and semi-arid regions, drought stress, low precipitation and water shortages are common during wheat growing seasons. These factors impact wheat performance by reducing plant growth variables and disrupting crop water relations, limiting root system development and changing biological functions like respiration and photosynthesis, which in turn affect the yield of wheat, quality of grain and water productivity (9). There are several reports of a water shortage in the world's wheat production. There are now extremely few water resources accessible for irrigation, thus it's crucial to figure out how to use the limited water available to get the most advantage per unit of water (10). To maintain sustainable wheat production and increase water productivity, water-saving irrigation principles and technologies must be developed (11). Many water-saving irrigation patterns for winter wheat have become popular due to the growing scarcity of water. Different irrigation techniques and scheduling control various components of wheat physiology, which have varying impact on the growth of wheat and water use. By managing the relationship between vegetative and reproductive growth, deficit irrigation technology can preserve or even increase production while conserving water (12,13) To increase agricultural output and water productivity, the deficit irrigation schedule must be done properly. Reducing water losses while preserving or increasing yield can be achieved by controlling the quantity and frequency of irrigation water, as well as by scheduling irrigation during periods when crop demand is highest (14). The volume of irrigation determines how well irrigation scheduling works in deficit irrigation. Increases in irrigation amount have been shown in some studies to increase stomatal conductance (Gs), photosynthesis and leaf water potential (15). However, long irrigation intervals and large irrigation amounts create a stress cycle of water deficit and excess water supply, which temporarily increases Gs and transpiration immediately after irrigation and decreases leaf water potential and photosynthesis before the next irrigation (16). Thus, limited irrigation supply at appropriate and most critical stages of the crop cycle is most essential to sustain wheat production (17).

Different elements in wheat cultivation contribute to increased production, including the adoption of high yielding cultivars, fertilizers and irrigation. Irrigation is an essential component for plant growth and development. The reduction in grain yield is also determined by the genotypes cultivated and the physiological phase of the plant at which moisture stress occurs (18). Various wheat genotypes exhibit varying water requirements in the ecosystems of Madhya Pradesh. There is insufficient irrigation water to meet the wheat crop's needs under the changing rainfall and distribution scenario. Crop yield is heavily dependent on genotypes. The selection of the appropriate wheat genotype increases crop productivity by approximately 20-25 % (19). Any wheat genotype that has previously been suggested for widespread cultivation in a specific region must be evaluated for its potential, overall stress tolerance and responsiveness to water (20).

The benefits of foliar fertilizer application include its quick action, effectiveness, affordability, ease of usage and efficiency of plant absorption (21). According to studies, foliar nutrient applications can improve grain yield and quality parameters by efficiently increasing the uptake of macro-elements like nitrogen, phosphorus and potassium, as well as vital micronutrients like iron, zinc and manganese (22). Additionally, foliar fertilization can be particularly beneficial in mitigating environmental stresses and nutrient deficiencies, which are common in wheat-growing regions (23, 24). The timing of foliar fertilizer treatment is crucial for achieving optimal outcomes (25). Wheat's phenological stages, such as tillering, stem elongation and flowering, have varied nutrient demands and fertilizer application during these critical growth stages can have a substantial impact on plant development and production. Previous studies have shown that stage-specific foliar fertilization improves biomass accumulation, filling of grain and nutrient translocation inside the plant (26). However, there is no clarity on the optimal phenological stage for foliar spray to maximize wheat production and quality under controlled irrigation conditions. Potassium is an essential macronutrient for plant growth and appropriate potassium supply, especially KCl treatment, can result in improved plant growth, tiller number and eventually, grain yield (27). Potassium boosts the quality and amount of productivity, particularly under moisture stress conditions, due to its regulatory role in stomatal opening and closing. Adequate potassium intake can also promote drought tolerance in wheat (28). Combining deficit irrigation with potassium chloride treatment can lead to increased grain production and improved irrigation water productivity (29). Furthermore, ascorbic acid application as a foliar spray improved wheat seedlings in overcoming the adverse effects of oxidative stress by sustaining growth, relative water content, cell membrane stability, osmotic adjustment via proline accumulation and by enhanced activity of antioxidant enzymes (30).

Foliar application of several stress regulators has been shown in prior studies to improve nutrient translocation, biomass accumulation and grain filling in plants (31). However, there is limited consensus on the concentration of chemicals and the most effective phenological stage for foliar application to maximize wheat yield and quality under controlled irrigation conditions. Thus, the goal of this study is to determine the best concentrations of KCl and Ascorbic acid to use at various phenological phases on wheat cultivars under deficit irrigation conditions.

Materials and Methods

Experimental site and climatic conditions

A wheat field trial was carried out during Rabi 2021-22 at the Jawaharlal Nehru Krishi Vishwa Vidyalaya's research farm in Jabalpur, Madhya Pradesh. The investigation site was at latitude 23.90°N and longitude 79.48°E, 411 m above MSL. During the cropping season, the mean weekly maximum and minimum temperatures were recorded at 40.60 °C and 3.90 °C. The total rainfall obtained during the growing season was 53.5 mm, with seven rainy days. The average relative humidity varied from 58 to 93 % in the morning and from 13 to 69 % in the evening.

Soil parameters

The soil at the start of the investigation had a sandy clay loam texture, medium soil organic carbon (0.67 %), available nitrogen (268.20 kg/ha), available phosphorus (19.50 kg/ha) and high available potassium (298.40 kg/ha), with a neutral pH (7.2).

Materials used

Two varieties were selected for the experimental study during *Rabi* 2021-22. Variety JW3288 released in 2010 matures in 120 -122 days with an average yield of 45-47 q/ha. The variety produces bold grains, is non-lodging and non-shattering, with profuse tillering and is a rust-resistant variety. It can be adopted in Central India under rainfed/restricted irrigated conditions. Variety JW 3382, released in 2015, is a multiple-resistant and heat-tolerant variety maturing in 119 days with an average yield of 59.75 q/ha. It can be adopted in Central India under irrigated, timely sown conditions. It is also rich in iron, zinc and protein and suitable for chapatti making. Both varieties are released by JNKVV. Two stress regulators, KCl and Ascorbic acid, were also used.

Treatment details

The experiment used a split-split plot design with three replications on an 8 m × 3.80 m (30.4 m^2) plot area. Three levels of irrigation (I1: one irrigation at CRI stage, I2: two irrigations at CRI and flowering stages and I3: three irrigations at CRI, flowering and milking stages) were assigned to the main plot and two wheat varieties (V1: JW3288 and V2: JW3382) were assigned to sub plot treatments, as well as five levels of foliar spray of stress regulators (F1: Control, F2: KCl @ 1 %, F3: KCl @ 2 %, F4: Ascorbic acid @ 0.1 % and F5: Ascorbic acid @ 0.2 %). During the tillering and flowering stages, stress regulators were sprayed on the foliage. The wheat crop was sown at the recommended seed rate of 100 kg/ha, with a row spacing of 22.5 cm. The initial irrigation was applied immediately after sowing. Following that, irrigations were performed following the treatment plan.

Observations recorded

Wheat cultural methods were followed and plant samples of one-meter row length were selected at random from the middle rows of each plot from three replicates to measure plant height (cm) and number of tillers/m row length at 60 DAS of the crop. Five continuous plants are selected from the field and placed in an electric oven at 80 °C for approximately 48 hr until a consistent weight is reached. The dry weight of each plant was assessed and the average weight is shown as g/plant. The leaf area index measures the proportion of leaf area to ground area. It calculates the quantity of assimilatory surface area taken up by plants. At harvest, observations were made on the yield characteristics, yield and economics of wheat.

Statistical analysis

The study results were presented as mean ± standard error. Using the statistical techniques available in R (R Studio, 4.3.1), a two-way analysis of variance (ANOVA) was performed to evaluate the degree of significance at the 5 % level. The treatment was assessed using the F test and critical difference (CD) values at P=0.05 were used to determine the importance of differences in mean treatment values (32).

Results

Plant height (cm)

Irrigation levels, varieties and foliar applications significantly ($p \leq 0.05$) influenced plant height (Table 1). The tallest plants were recorded under I3 (three irrigations at CRI+FS+MS), which was 7.0 % and 4.3 % higher than I1 (one irrigation at CRI) and I2 (two irrigations at CRI+FS), respectively and all differences were statistically significant. Among varieties, V1 (JW 3288) had significantly greater plant height than V2 (JW 3382), with a 5.6 % increase. Regarding foliar applications, F2 (1 % KCl) and F3 (2 % KCl) were statistically at par and both were significantly superior to the control. These treatments resulted in the tallest plants, with 1 % KCl showing a 9.5 % increase over the control. Treatments with F4 (0.1 % ascorbic acid) and F5 (0.2 % ascorbic acid) also enhanced plant height by 4.8 % and 6.5 %, respectively over the control. The interaction effects (IRR × VAR, VAR × FA, IRR × FA) were statistically significant ($p \leq 0.05$), confirming interactive contributions of variety and foliar application under different irrigation regimes.

Number of tillers (m^{-2})

Tillering capacity improved significantly ($p \leq 0.05$) under better irrigation levels, varieties and foliar application of stress regulators (Table 1). The maximum number of tillers was recorded under I3 (three irrigations at CRI+FS+MS), which was 24.6 % higher than I1 (one irrigation at CRI) and 13.6 % higher than I2 (two irrigations at CRI+FS) and all differences were statistically significant. Among varieties, V1 (JW 3288) produced 12.7 % more tillers than V2 (JW 3382) and the difference was substantial. Among foliar applications, the highest number of tillers was observed under F3 (2 % KCl), showing an 11.9 % increase over the control, followed by F2 (1 % KCl) (9.3 % increase). The ascorbic acid treatments were also at par with each other and F5 (0.2 % AA) showed a statistically significant advantage over the control. All two-way interactions were statistically significant ($p \leq 0.05$), with the best performance observed under CRI+FS+MS × JW 3288 × 2 % KCl.

Total dry matter accumulation (g/plant)

The effect of irrigation levels, varieties and foliar applications on the total dry matter accumulation (DMA) was significant at the 5 % probability level (Table 1). I3 (three irrigations at CRI+FS+MS) recorded the highest DMA, representing an increase of 50.8 % over I1 (one irrigation at CRI) and 18.7 % over I2 (two irrigations at CRI+FS). Among varieties, V1 (JW 3288) accumulated 6.6 % more biomass than V2 (JW 3382), which was significant. Among foliar treatments, 2 % KCl (4.66 g $plant^{-1}$) and 1 % KCl (4.40 g $plant^{-1}$) increased DMA by 23.9 % and 17.0 %, respectively, over the control (3.76 g $plant^{-1}$). While F5 (0.2 % AA) and F4 (0.1 % AA) were at par with each other and intermediate in effect. All interaction terms were significant ($p \leq 0.05$) and the combination CRI+FS+MS × JW 3288 × 2 % KCl resulted in the maximum biomass accumulation.

Leaf area index (LAI)

LAI values were significantly ($p \leq 0.05$) affected by irrigation levels, varieties and foliar applications (Table 1). I3 (three irrigations at CRI+FS+MS) recorded the highest LAI, which was 47.6 % and 20.5 % greater than I1 (one irrigation at CRI) and I2

Table 1. Influence of irrigation levels, varieties and foliar application on growth and physiological parameters in wheat at 60 DAS

Treatments	Plant height (cm)	No. of tillers/m²	Total DMA (g/plant)	LAI
		Irrigation levels		
CRI	61.19 b	354.7 c	3.33 c	1.91 c
CRI+FS	62.71 b	389.1 b	4.23 b	2.34 b
CRI+FS+MS	65.44 a	441.9 a	5.02 a	2.82 a
SEm±	0.58	8.52	0.02	0.04
CD (*p*<0.05)	2.29	33.45	0.10	0.17
		Varieties		
JW 3288	64.83 a	418.8 a	4.33 a	2.44 a
JW 3382	61.40 b	371.7 b	4.06 b	2.27 b
S.Em±	0.44	3.03	0.01	0.02
CD (*p*<0.05)	1.52	10.51	0.05	0.07
		Foliar applications		
Control	59.64 d	371.1 c	3.76 e	2.17 e
1 % KCl at TS+FS	65.31 a	405.7 a	4.40 b	2.43 b
2 % KCl at TS+FS	64.61 ab	415.3 a	4.66 a	2.54 a
0.1 % AA at TS+FS	62.51 c	385.6 bc	4.00 d	2.28 d
0.2 % AA at TS+FS	63.49 bc	398.3 ab	4.16 c	2.37 c
S.Em±	0.54	6.82	0.02	0.01
CD (*p*<0.05)	1.54	19.40	0.07	0.04
		Interactions		
IRR x VAR	2.63	18.21	0.08	NS
VAR x FA	2.31	27.44	0.10	NS
IRR x FA	2.90	33.61	0.12	NS
IRR x VAR x FA	3.77	47.53	0.17	NS

LAI: Leaf area index, CRI: irrigation at crown root initiation stage, CRI+FS: irrigations at CRI and flowering stages, CRI+FS+MS: irrigations at CRI, flowering and milking stages, Control (only water spray), KCl: Potassium chloride, AA: Ascorbic acid, TS+FS: Tillering and flowering stages, NS: Non-significance

(two irrigations at CRI+FS), respectively. Among varieties, V1 (JW 3288) showed 7.5 % higher LAI than V2 (JW 3382), significant at p ≤ 0.05. Among foliar treatments, F3 (2 % KCl) enhanced LAI by 17.1 %, while 1 % KCl improved it by 12.0 % over the control treatment, respectively. Both ascorbic acid treatments were also statistically equal. Interaction effects were not significant (p ≥ 0.05) for LAI.

Effective tillers (m^{-2})

The effect of irrigation levels, varieties and foliar applications on the total effective tillers was significant at the 5 % probability level (Table 2). I3 (three irrigations at CRI+FS+MS) had the maximum number of effective tillers, which was 22.8 % higher than I1 (one irrigation at CRI) and 8.2 % higher than I2 (two irrigations at CRI+FS). Treatment V1 (JW 3288) produced 17.1 % more effective tillers than V2 (JW 3382) among varieties. Application of F3 (2 % KCl) was significantly superior to all other foliar treatments, resulting in the highest effective tillers and showing a 12.7 % improvement over the control treatment. Significant interaction effects (p ≤ 0.05), especially IRR × FA, demonstrated that irrigation efficacy was enhanced when coupled with varietal performance and foliar application, leading to maximum tillering in CRI+FS+MS × JW 3288 × 2 % KCl.

Test Weight (g)

Grain test weight was significantly (p ≤ 0.05) influenced by treatments (Table 2). Test weight was highest under I3 (three irrigations at CRI+FS+MS), significantly superior to I1 (one irrigation at CRI) and I2 (two irrigations at CRI+FS), with a maximum increase of 8.1 %. Among varieties, V1 (JW 3288) had 3.8 % higher test weight than V2 (JW 3382). Among foliar treatments, F3 (2 % KCl) and F2 (1 % KCl) were statistically at par, both outperforming the control by 6.3 % and 4.4 %, respectively. All interaction effects were statistically significant (p ≤ 0.05), with IRR × FA showing the most significant variation. The highest test weights were recorded under CRI+FS+MS × JW 3288 × 2 % KCl.

Grain yield (t/ha)

Grain yield was significantly (p ≤ 0.05) affected by treatments (Table 2). Grain yield was significantly improved with enhanced irrigation levels. Treatment I3 (three irrigations at CRI+FS+MS) showed an increase of 52 % grain yield over I1 (one irrigation at CRI) and 15.7 % grain yield over I2 (two irrigations at CRI+FS). Treatment V1 (JW 3288) had a 12.7 % higher grain yield than V2 (JW 3382) among varieties. Among foliar applications, F3 (2 % KCl) and F2 (1 % KCl) differed significantly from the control, reflecting 33.2 % and 19.7 % more grain yield, respectively. Ascorbic acid treatments were intermediate and statistically at par with each other. All interaction effects were statistically significant (p ≤ 0.05), with the IRR × FA interaction producing a maximum variation. The CRI+FS+MS × JW 3288 × 2 % KCl treatment combination achieved the highest grain yield.

Straw yield (t/ha)

Straw yield data were statistically significant (p ≤ 0.05) among the different treatments (Table 2). I3 (three irrigations at CRI+FS+MS) recorded the maximum straw yield, which was 35.6% higher than I1 (one irrigation at CRI) and 13.9 % higher than I2 (two irrigations at CRI+FS). Among varieties, V1 (JW 3288) outperformed V2 (JW 3382) and produced 10.2 % more straw. Foliar application of F3 (2 % KCl) yielded 22.2 % more straw than the control, followed by F2 (1 % KCl) with a 13.6 % increase. All two-way interactions were significant (p ≤ 0.05), with the IRR × FA interaction contributing the most significant difference. The most productive straw biomass was observed in the CRI+FS+MS × JW 3288 × 2 % KCl combination.

Table 2. Influence of irrigation levels, varieties and foliar application on yield attributes, yield and economics in wheat

Treatments	Effective tillers/m²	Test weight (g)	Grain yield (t/ha)	Straw yield (t/ha)	B: C ratio
		Irrigation levels			
CRI	373.5 c	40.8 c	2.82 c	4.35 c	1.60
CRI+FS	423.7 b	42.2 b	3.70 b	5.18 b	2.28
CRI+FS+MS	458.6 a	44.1 a	4.28 a	5.90 a	2.71
SEm±	6.54	0.47	0.06	0.07	-
CD (p<0.05)	25.69	1.83	0.25	0.29	-
		Varieties			
JW 3288	451.7 a	43.2 a	3.81 a	5.39 a	2.39
JW 3382	385.6 b	41.6 b	3.38 b	4.89 b	2.02
S.Em±	3.15	0.32	0.03	0.03	-
CD (p<0.05)	10.90	1.10	0.12	0.12	-
		Foliar applications			
Control	394.4 d	41.2 c	3.10 d	4.64 d	2.00
1 % KCl at TS+FS	430.2 ab	43.0 b	3.71 b	5.27 b	2.30
2 % KCl at TS+FS	444.4 a	43.8 a	4.13 a	5.67 a	2.36
0.1 % AA at TS+FS	407.3 cd	41.7 bc	3.36 c	4.92 c	2.12
0.2 % AA at TS+FS	416.7 bc	42.2 b	3.69 b	5.21 b	2.23
S.Em±	5.22	0.56	0.05	0.06	-
CD (p<0.05)	14.84	1.59	0.15	0.19	-
		Interactions			
IRR x VAR	18.89	1.91	0.27	0.30	-
VAR x FA	20.81	2.26	0.22	0.26	-
IRR x FA	29.58	2.76	0.30	0.36	-
IRR x VAR x FA	36.37	3.91	0.38	0.47	-

B: C ratio: Benefit cost ratio, CRI: irrigation at crown root initiation stage, CRI+FS: irrigations at CRI and flowering stages, CRI+FS+MS: irrigations at CRI, flowering and milking stages, Control (only water spray), KCl: Potassium chloride, AA: Ascorbic acid, TS+FS: Tillering and flowering stages

Economics

Among irrigation levels, economic efficiency was highest under I3 (three irrigations at CRI+FS+MS), recorded 69.4 % and 18.9 % greater returns than I1 (one irrigation at CRI) and I2 (two irrigations at CRI+FS), respectively (Table 2). Among varieties, V1 (JW 3288) had an 18.3 % higher benefit than V2 (JW 3382). Among foliar applications, F3 (2 % KCl) recorded the highest B: C ratio, 18.0 % greater than the control, with F2 (1 % KCl) showing a 15.0 % more profit.

Correlation among growth and yield parameters

The analysis revealed a strong and positive correlation between grain yield and associated traits such as straw yield, effective tillers per square meter and total dry matter accumulation (Fig. 2). The prominent size and deep coloration of the pie segments representing these parameters indicate a high degree of association, suggesting that improvements in vegetative growth components directly contributed to enhanced yield performance. Notably, effective tiller number showed a robust correlation with both total dry matter and grain yield, underscoring its role as a key yield-determining trait. These findings highlight the integrative impact of physiological growth on final yield outcomes and affirm the potential of strategic irrigation and foliar applications in synchronizing growth dynamics for yield optimization.

Discussion

The present study demonstrated that irrigation scheduling, varietal selection and foliar applications of stress-regulating compounds such as potassium chloride (KCl) and ascorbic acid (AA) exerted profound individual and interactive effects on wheat growth parameters, yield components, productivity and economic returns. The outcomes highlight the significance of synchronizing crop water demand with strategic agronomic interventions to sustain wheat productivity under fluctuating moisture regimes (Fig. 1).

The superior performance of the I3 (three irrigations at CRI+FS+MS) irrigation schedule in enhancing growth parameters such as plant height, tiller number, dry matter accumulation (DMA) and leaf area index (LAI) can be attributed to sustained soil moisture availability during the critical stages of wheat. Adequate moisture at these stages promotes cell division, cell elongation and photosynthetic activity by maintaining turgor and chlorophyll stability (33). Previous studies have confirmed that irrigation applied at the milking stage (MS) effectively prolongs the green leaf area duration, thereby facilitating enhanced photosynthate production and translocation to the developing grains (34). This aligns with findings by (35) who reported an 18-20 % increase in biomass and grain yield with supplemental irrigation at reproductive stages in wheat.

Significantly higher tiller production under improved irrigation is consistent with earlier observations by (36) indicating that optimal soil moisture conditions during crown root initiation (CRI) and later stages facilitate axillary bud outgrowth and reduce tiller mortality. Effective tiller survival is a function of resource availability and hormonal regulation, particularly cytokinins, whose synthesis and translocation are enhanced by adequate root-zone moisture.

The genotypic superiority of JW 3288 over JW 3382 for growth and yield components, particularly under moisture stress, suggests inherent differences in drought avoidance and tolerance traits. JW 3288 likely possesses greater root system development, higher stomatal conductance

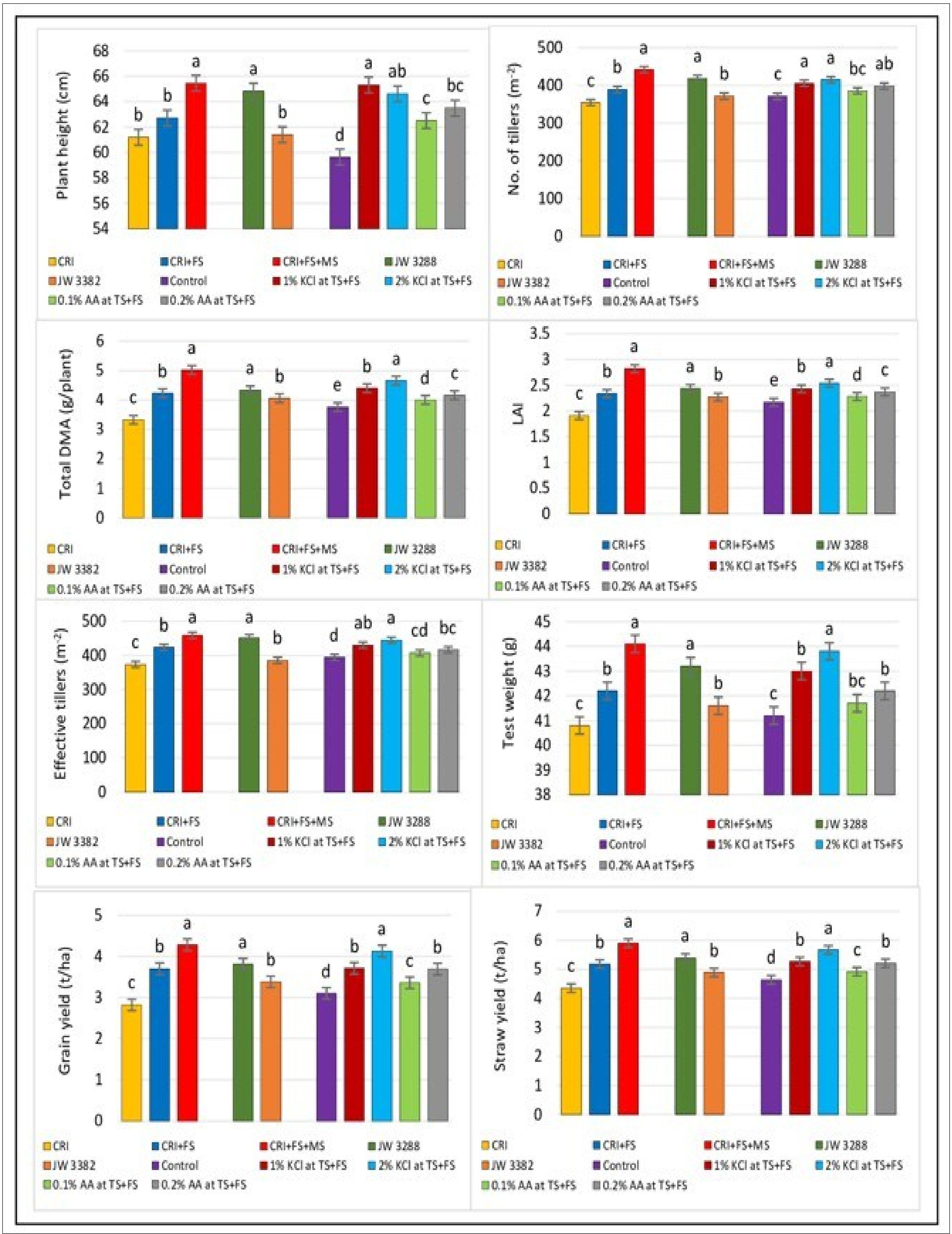

Fig. 1. Interactive effect of irrigation levels, varieties and foliar applications on growth parameters, yield attributes and yield. Bars represent mean values with standard error (SE). Treatments marked with different lowercase letters differ significantly at P ≤ 0.05 according to Duncan's Multiple Range Test (DMRT), indicating statistically significant differences among treatments. CRI, CRI+FS and CRI+FS+MS indicate the irrigation at CRI, CRI and flowering, and CRI, flowering and milking stages, respectively. TS and FS indicate the foliar application at the tillering and flowering stages.

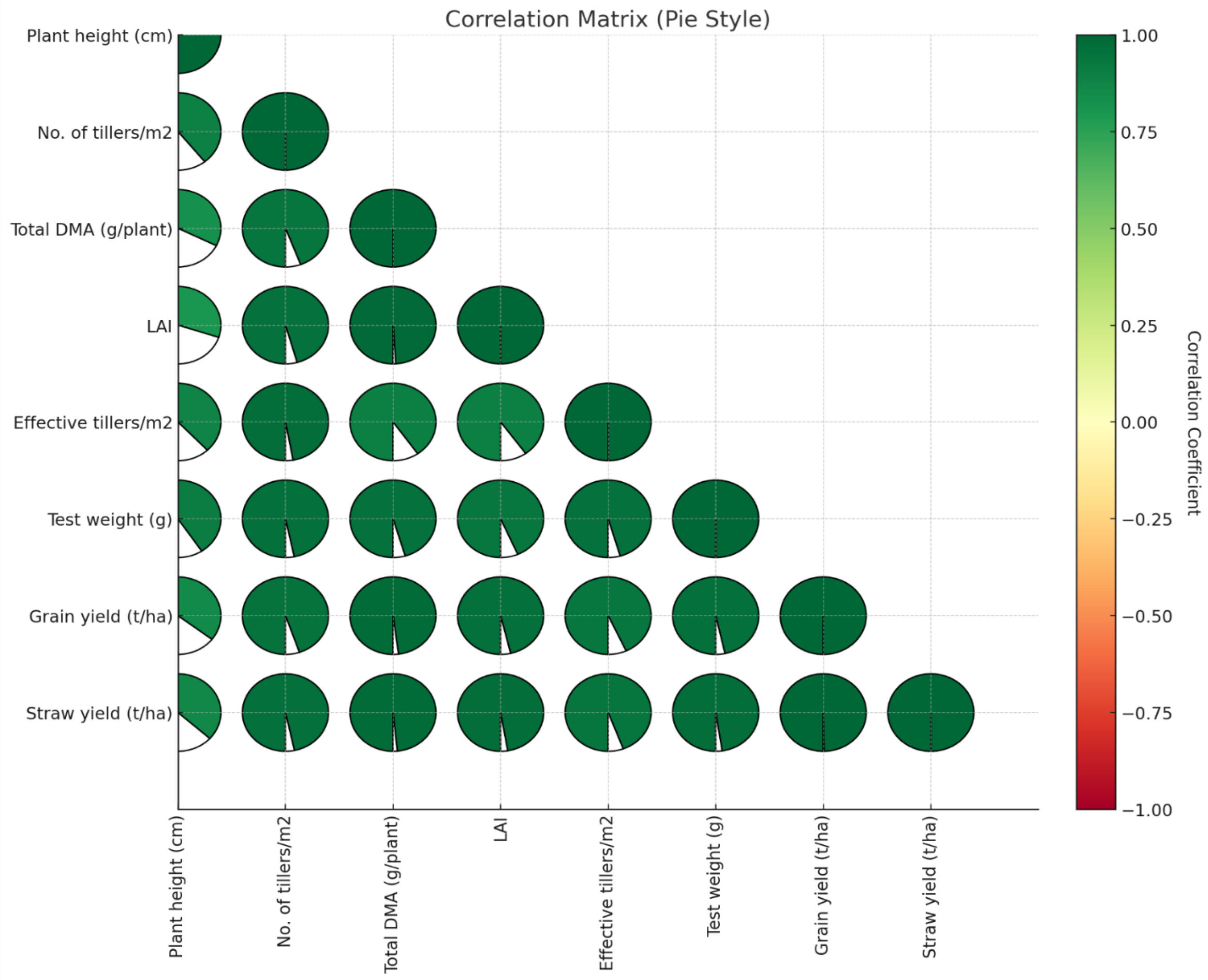

Fig. 2. Correlation matrix (pie-style) depicting Pearson's correlation coefficients among growth and yield parameters in wheat under different irrigation levels, varieties and foliar applications. The size of the pie sector represents the strength of correlation, while the colour indicates its direction and magnitude. Strong positive correlations were observed between grain yield, straw yield, effective tillers and total dry matter accumulation.

regulation and more efficient photosynthate partitioning under sub-optimal moisture availability. Similar genotypic variation in wheat response to water stress has been widely documented (37), emphasizing the role of breeding for drought resilience in rainfed and moisture-limited systems. The ability of JW 3288 to accumulate higher DMA and maintain greater LAI indicates superior canopy longevity and photosynthetic productivity, which are essential for achieving higher yield potential (38).

Foliar application of ascorbic acid (AA) demonstrated moderate but significant improvements in growth and yield parameters under limited moisture conditions(39). Ascorbic acid functions as a non-enzymatic antioxidant, mitigating reactive oxygen species (ROS) accumulation, stabilizing chloroplast structures and prolonging leaf functional duration during stress (40, 41). The improved LAI and DMA under AA treatments may be linked to enhanced chloroplast stability, prolonged leaf area duration and increased photosynthetic activity (42). Although its yield benefits were comparatively lower than KCl, ascorbic acid plays a vital role in enhancing plant resilience under stress conditions, which is critical in semi-arid wheat production systems (43).

The significant improvement in yield attributes and grain yield with foliar application of potassium chloride (KCl), especially at 2 % concentration, can be explained by the crucial role of potassium in regulating stomatal regulation, osmotic adjustment, assimilate translocation and maintaining cell turgor during water deficit conditions (44). By stabilizing leaf water relations and delaying senescence under fluctuating moisture regimes, application of KCl at critical stages likely maintained photosynthetic capacity, enhanced assimilate translocation and improved grain filling, contributing to higher test weight and yield (45). Potassium also activates over 60 enzymatic systems involved in carbohydrate metabolism and enhances the conversion of photosynthates into starch during the grain filling phase (46). The increase in test weight and grain yield under KCl application agrees with earlier findings by (47), who reported that potassium supplementation enhances kernel weight by improving grain filling duration.

The significance of interaction effects among irrigation, variety and foliar stress regulators highlights the importance of integrated moisture stress management strategies. The highest productivity and profitability were achieved when optimal irrigation (three irrigations at CRI+FS+MS) was combined with a responsive variety (JW 3288) and foliar-applied KCl at 2 %. This combination effectively aligned plant water requirements with moisture availability and physiological regulation of stress responses, confirming earlier findings by (48) who demonstrated synergistic effects of drought-mitigation practices in wheat.

In terms of economic returns, the enhanced Benefit-Cost (B: C) ratios under I3 (three irrigations at CRI+FS+MS) and KCl foliar applications indicate that while additional investments in water and stress regulators increase operational costs, the resultant yield and economic gains substantially justify these inputs. This aligns with previous work, which concluded that strategic stress management interventions in wheat are not only agronomically effective but also economically viable.

While ascorbic acid improved yields relative to the control, its economic advantage was comparatively less due to smaller yield increments. Nevertheless, its protective role in improving plant resilience during transient stress periods remains highly relevant for semi-arid wheat systems prone to mid-season stress events (49). Since water availability during critical growth stages is often uncertain in wheat-growing areas, especially in semi-arid and rainfed regions, using ascorbic acid sprays during sensitive stages could help plants withstand short-term moisture stress and maintain better growth and grain development when irrigation is not always possible (50).

Conclusion

The present investigation confirmed that precise irrigation scheduling, variety selection and foliar application of stress regulators effectively mitigate moisture stress in wheat. Irrigation at crown root initiation, flowering and milking stages (CRI+FS+MS) significantly improved growth parameters, yield attributes and economic returns by ensuring moisture availability during physiologically sensitive phases. Variety JW 3288 demonstrated superior adaptability and yield performance over JW 3382 across moisture regimes. Foliar application of 2 % potassium chloride notably alleviated moisture stress effects, sustaining leaf water status and enhancing grain development, while ascorbic acid provided less but beneficial stress protection. The interaction of applying three irrigations at CRI+FS+MS stages with foliar application of 2 % KCl in the JW 3288 variety consistently produced the highest productivity and profitability. These findings underscore the importance of integrated crop, water and foliar stress management strategies to enhance wheat performance and resilience under moisture-limited agro-ecological conditions.

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Authors' contributions

BV and AKJ participated in conceptualization, writing of original draft, visualization, methodology, investigation, statistical analysis and supervision. RSR participated in methodology, resources, supervision and data curation. NS, RD, RP, AD, PSY and MP reviewed, edited and validated the manuscript. All authors read and approved the final manuscript.

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