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Original Research

Gas Exchange Characteristics, Water Relations, and Irrigation Water Use Efficiency of Wheat Influenced by Potassium Nutrition Under Water-Limited Conditions

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Abstract

Potassium is an essential nutrient that contributes to the survival of wheat once subjected to water deficit conditions. A field trial was conducted using a randomized complete block design with split-plot arrangements. Different water regimes, including well-watered and water-deficit conditions at the tillering stage, were maintained in the main plot. Subplot treatments included no potassium; soil applied the recommended dose of potassium, distilled water spray, 1% potassium spray, and 2% potassium spray, respectively. A significantly higher value of gas exchange characteristics, water relations, and wheat yield was recorded with the foliar application of potassium than those of the control. The foliar spray of 2% potassium was superior to soil-applied potash under water deficit conditions, with a 25.33% improvement in grain yield of wheat. Similarly, a 47.58% and 25.76% improvement in grain yield of wheat was recorded with 2% and 1% potassium spray as compared to that of distilled water spray under

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water deficit conditions. The chlorophyll content, cell membrane stability, relative water content, net photosynthetic rate, stomatal conductance, and transpiration rate were 21.5%, 26.07%, 2.79%, 84.41%, 13.84%, and 10%, respectively. Irrigation water use efficiency under drought conditions was 51.02% higher with a 2% foliar spray of potash than in well-watered conditions where potassium was not applied. The benefit-cost ratio was recorded as 1.24 and 1.30 with 2% foliar application of potassium and soil-applied potassium, respectively. Our findings displayed that a 2% foliar spray of potash can be utilized under water deficit conditions for improvement of grain yield, whereas soil application of potash can be utilized with additional benefits.

Keywords: drought, grain yield, net photosynthesis, fertilizer use efficiency, *Triticum aestivum* L.

Introduction

Scarcity of water at critical crop growth stages is directly linked with a reduction in its yield, with no exception to wheat [1]. Water use efficiency is even a matter of serious concern, particularly under arid or semi-arid environmental conditions [2], where crop production suffers negatively. The sufficient supply of potassium to plants makes them less sensitive to acute water deficits by maintaining turgor, water contents, and osmoregulation. An increase in potassium requirement by plants has been reported under drought conditions [3-5].

Wheat (*Triticum aestivum* L.) is the staple food of 1.2 billion people worldwide [6-8]. It has gained a prime position among cereals owing to food security concerns and its crucial role in world trade. Increasing wheat production to meet the higher demands of rising populations is still a challenge in many countries [9], as food security is a major global concern [10]. With the increasing global population, the demand for wheat is expected to increase by 40% by 2050 [11, 8]. There are regional differences in the grain yield of wheat due to variations in crop management practices and agro-ecology conditions [12]. Moreover, in most developing countries, the yield of wheat is lower than that in developed countries. Many factors are responsible for the low yield of wheat, including the cultivation of old varieties, late sowing, poor seed quality, imbalanced fertilization, and water scarcity. Moreover, plants require a balanced supply of nutrients throughout their growth and developmental stages [13, 14].

Among the different stressors, drought is the most alarming, affecting agricultural productivity worldwide [15, 16]. Water deficit, particularly at the vegetative stage, results in a lower yield [17]. Plant growth and biochemical and physiological processes are impaired under drought conditions [18]. The enhancement of crop productivity under limited water availability is a major challenge in modern agriculture. Pakistan is among the 36 countries affected by water shortages [19, 20]. Moreover, non-judicious irrigation practices have led to a continuous lowering of the water table in Pakistan [21]. Multiple strategies have been adopted to grow crops under water-deficit conditions, including the use of drought-tolerant varieties, different water management strategies, and foliar application of bio-regulators [22, 23]. Different osmo-protectants have been utilized effectively to alleviate the harmful effects of water deficits [24]. An adequate supply of water and nutrients is required to enhance crop productivity and achieve the highest potential yield of a particular crop [25, 26, 14]. Potassium is the primary essential nutrient that helps regulate plant growth, survival, cell evolution, and maintenance of the ionic balance within the plant cells. It activates photosynthetic enzymes, enhances protein synthesis, and maintains cell turgidity [27, 28]. The beneficial role of potassium in plants exposed to abiotic stresses includes physiological mechanisms associated with photosynthesis, stomatal conductance, and osmo-protection [29]. Depletion of potassium is a major reason for the degradation of arable land in Southeast Asia, Latin America, and the Caribbean. Agriculture in Central Europe is oriented towards potassium mining and is the principal reason for low water-use efficiency, resulting in considerable seasonal variability in yields [30]. In Pakistan, the use of fertilizers is unbalanced; nitrogen usage is satisfactory, phosphorus usage is inadequate, and potassium is only nominal [31]. The average usage of potassium in Pakistan is approximately 0.8 kg ha-1 against 15 kg ha-1 globally [32]. Deole et al. [33] reported that potassium at a substantial concentration serves as an osmo-protectant; moreover, stomatal movement is greatly dependent on potassium concentration [34].

Drought induces the accumulation of potassium in leaves. Most plants require an adequate amount of potassium to tolerate drought. Yield losses due to water-limiting conditions can be decreased by potassium application [35]. The uptake of potassium is limited to 1–2% in plants, whereas the rest is fixed in the soil [36]. Therefore, foliar spraying of potassium is more attractive and economical for improving fertilizer use efficiency and grain yield than soil application [37]. There are also contrasting reports on the efficacy of foliar application of potassium to wheat crops exposed to drought, as reported by various researchers [38-40]. Thus, the primary objective of the current study was to optimize the foliar fertilization of potassium to improve the physiological and yield performance and irrigation water use efficiency of spring wheat under water deficit conditions.

Table 1. Physico-chemical properties of soil from experimental site (15 cm depth).

Soil Characteristics	Contents
Soil texture	Loam
Saturation (%)	36
EC (dS/m)	1.65
Ph	8.3
Organic matter (%)	0.59
N (mg/kg soil)	17.3
P (mg/kg soil)	7.8
K (mg/kg soil)	140

Materials and Methods

Experimental Site

The field study was conducted at the research farm, MNS University of Agriculture, Multan, Pakistan (Longitude 71.5249°E, Latitude 30.1575°N) during the winter season of 2018-2019. The experimental soil was well drained and loam in texture. The soil physico-chemical properties are presented in Table 1.

Meteorological data during the course of studies was collected from the meteorological observatory of MNS University of Agriculture (MNSUA), Multan, and is shown in Fig. 1.

Experimental Design and Treatments

The trial was laid out in a Randomized Complete Block Design (RCBD) under split-plot arrangements with three replications. Different water regimes, including normal irrigation (W_1) and drought at tillering (GS-2 as per the Feekes scale) (W_2), were kept in the main plot, while different potassium levels, including T_1 = soil-applied recommended dose of potassium (124 kg ha^{-1}), T_2 = without soil-applied potassium, T_3 = distilled water spray, T_4 = 1% potassium spray, and T_5 = 2% potassium spray, were kept in the subplot. Drought was imposed by skipping irrigation at the tillering stage (GS-2 as per the Feekes scale) as a most water-sensitive stage (foliar spray of potassium was done by using potassium nitrate after 7 days of imposition of drought in respective treatments). A measured quantity of water was applied by using a cutthroat flume.

General Agronomic Practices

The wheat variety "Ujala-2016" was drilled in rows 22.5 cm apart. The seed rate was kept at 120 kg ha^{-1}. The recommended rates of nitrogen and phosphorus at 80 and 57 kg ha^{-1} were applied, respectively. The full dose of phosphorus was applied at the time of sowing, while half of the nitrogen was applied at the time of sowing and half with the first irrigation.

Recorded Data

Agronomic and Yield Traits

Plant height (cm), spike length (cm), spikelets per spike, and grains per spike were recorded from ten randomly selected plants from each experimental unit. The number of tillers, number of grains, and straw yield were calculated by harvesting an area of 1m^2.

Physiological Traits

Gas exchange characteristics were measured after one week of foliar application of different potassium levels after the imposition of drought. A fully expanded youngest leaf from each treatment plot was used to measure the net photosynthetic rate, transpiration rate, and stomatal conductance and was recorded with the help of the CIRAS-3 moveable photosynthesis system. Data were recorded during sunshine hours between

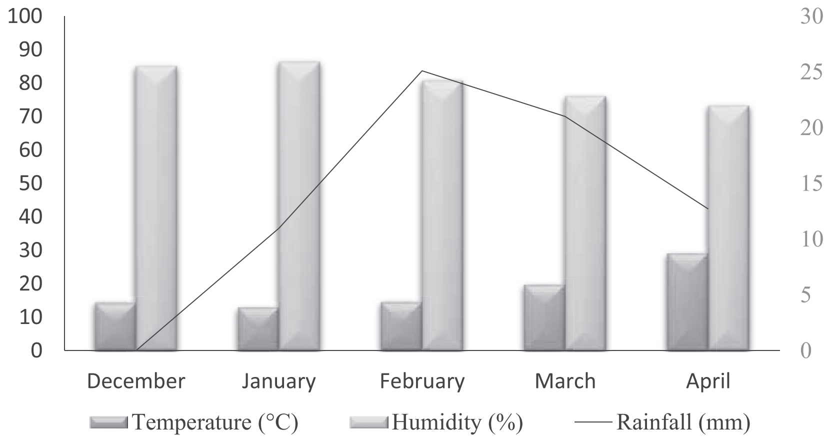


Fig. 1. Meteorological data (mean monthly) during the course of studies.

11:00 am and 1:00 pm. The chamber was adjusted at a 100 mL·min^{-1} air flow rate, 1200 μmol·m^{-2}·s^{-1} density of photosynthetic photon flux, 390 ± 5 μmol·mol^{-1} CO_2 concentration rate, and 99.9 kpa atmospheric pressure.

A SPAD-502 plus chlorophyll meter was used to determine the chlorophyll contents in leaves after one week of foliar application of potassium and after the imposition of drought. Cell membrane stability was determined after one week of foliar application of different potash levels after the imposition of drought. It was computed using the method proposed by Tuna *et al.* [41]. Relative water content in leaves was determined after seven days of foliar application of treatment after imposition of drought. It was computed using the formula proposed by Turner and Schutte [42].

$$RWC = \frac{Fresh\ weight - Dry\ weight}{Turgid\ weight - Dry\ weight} \times 100$$

Irrigation Water use Efficiency

Irrigation water use efficiency was calculated by utilizing formulas described by Monteith et al. [43].

$$Water\ Use\ Efficiency\ = \frac{BiologicalYield(kg\ ha^{-1})}{Water\ use\ by\ crop\ (mm)}$$

The data collected for various agronomic and yield traits were analyzed by using Fisher's analysis of variance technique, and differences between treatment means were compared by HSD Tukey's test at a 5% level of probability [44]. The relative profitability of different treatments was worked out as described in CIMMYT [45].

Results and Discussion

Potassium's Role in Improving Agronomic and Yield Traits in Wheat Exposed to Drought

Different potassium treatments significantly influenced the height of the wheat. The height of wheat was 2.59% higher under normal irrigation conditions than under water deficit conditions. The maximum plant height (119.05 cm) was observed in plots where 2% potassium spray was applied. This was similar to that achieved with the 1% potassium spray and soil applied with potassium. The minimum plant height (112.65 cm) was observed in plants sprayed with distilled water (Fig. S1). Regression analysis revealed a significant relationship between the plant height and grain yield. A strong positive linear association was observed between plant height and grain yield under normal irrigation (r = 0.963**) and drought conditions at GS-2 (r = 0.996**) (Fig. S2).

The interaction between the water regime and potassium treatment was significant for tillers m^{-2} of wheat. The maximum number of tillers m^{-2} (242.89) was observed under normal irrigated conditions in wheat, where a full dose of potassium was applied to the soil (Fig. S3). Minimum (195.66 m^{-2}) tillers m^{-2} were noted in experimental plots in which potassium was not applied under the skipped irrigation regime. Under water deficit at tillering (GS-2 as per the Feekes scale), 2% potassium spray displayed more highly significant results than the rest of the treatments by recording the maximum number of tillers m^{-2} (219.88 m^{-2}). A strong positive linear association was recorded between the number of tillers m^{-2} and the 1000-grain weight of wheat under normal irrigation (r = 0.986**) and drought conditions (r = 0.894**) (Fig. S4). Spike length was highest (13.06 cm) for wheat sprayed with 2% potassium, whereas the shortest spike length (12.53 cm) was observed in plots where potassium was not applied. The spike length of wheat was 3.02% higher under normal irrigation than under drought at GS-2, as per the Feekes scale (Fig. S5). Drought at the tillering stage resulted in fewer spikelet spike^{-1} in wheat than in the normal irrigation regime (Fig. S6). The maximum spikelet spike^{-1} (21.17) was observed in plants treated with 2% foliar spray of potassium, whereas a minimum (20.60) was observed in the treatment without potassium.

Grains spike^{-1} of wheat were significantly influenced by the interactive effect of W×K (Fig. S7). The maximum grain spike^{-1} (63.67 g) was observed under normal irrigation, whereas an exogenous application of 2% potassium was performed. The minimum grain spike^{-1} (51.83 g) was noted when potassium was not applied under drought-stress conditions at GS-2. A strong positive association was recorded between the number of grains per spike^{-1} and grain yield under normal irrigation (r = 0.987**) and drought at GS-2 (r = 0.944**) in wheat (Fig. S8). Different water regimes and potassium treatments significantly influenced the 1000-grain weight of wheat (Fig. S9). The maximum 1000-grain weight (32.74 g) was observed in the treatment where the recommended dose of potassium was applied to the soil. However, the same 1000-grain weight was recorded under both the 1% and 2% potassium sprays. A minimum 1000-grain weight (27.98 g) was observed when potassium was not applied to the soil.

The grain yield was 8.98% lower under drought conditions than under normal irrigation (Fig. 2). The different potassium treatments significantly influenced the grain yield of wheat. Grain yield was the highest (4.87 t ha^{-1}) in the case of 2% foliar potassium spray, whereas the minimum grain yield (3.18 t ha^{-1}) was observed when potassium was not applied. A strong positive linear association was observed between plant height and grain yield, as well as grains per spike and grain yield under normal irrigation and drought at GS-2 as per the Feekes scale (Table 2).

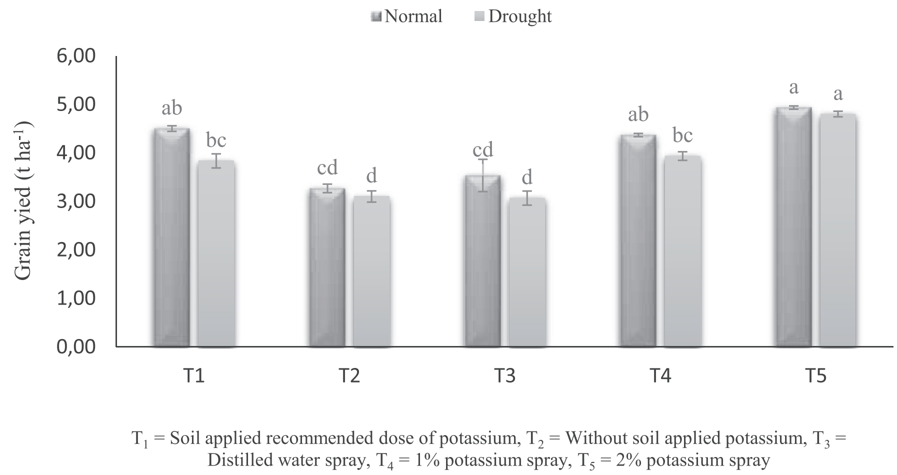


Fig. 2. Grain yield (t ha^{-1}) of wheat as influenced by the application of potassium under different irrigation regimes.

Significant impacts of different water regimes on wheat straw yield were recorded. Optimum water supply resulted in 17.04% more straw yield compared to drought at the tillering stage (GS-2 as per the Feekes scale) (Fig. S10). Straw yield was highest (13.77 t ha^{-1}) with 2% foliar spray of potassium, whereas a minimum (9.77 t ha^{-1}) was observed in plots where potassium was not applied.

Potassium's Role in Improving Physiological Traits in Wheat Exposed to Drought

Drought stress significantly decreased chlorophyll content in wheat (Fig. S11). Under drought conditions, chlorophyll content was recorded lower than that under normal irrigation conditions. The maximum chlorophyll content (46.73) was observed under normal irrigated conditions, which was 9.36% higher than that achieved under water deficit conditions. The chlorophyll content was significantly influenced by the interactive effects of potassium and water regimes. The highest chlorophyll content (55.07) was observed in plants under normal irrigation, whereas potassium was applied in the soil, which was similar to that in plants treated with 2% foliar spray of potassium; the lowest chlorophyll content (37.80) was observed in the treatment where potassium was not used in the soil.

The interaction between potassium and water regimes was statistically significant for the cell membrane stability of wheat (Fig. S12). The highest cell membrane stability (84.46%) was noted in soil treated with potassium, and this was similar to that of treatment with 2% potassium foliar spray under normal irrigation conditions. The lowest cell membrane stability (46.95%) was observed in plots with soil without potash application under water deficit, and it was statistically similar to distilled water spray under both normal and water deficit conditions and to soil without potassium application under normal irrigation.

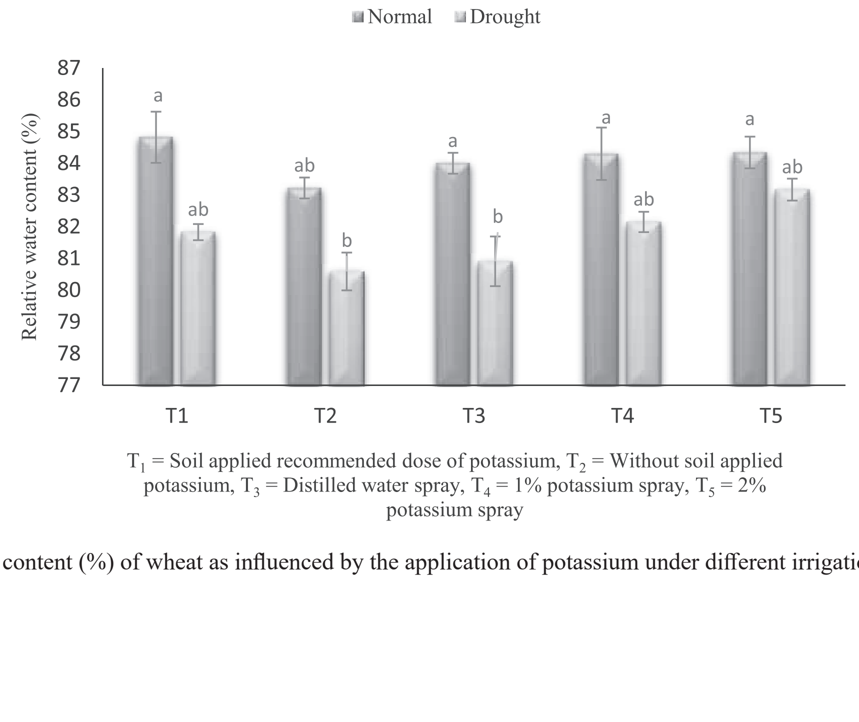


Fig. 3. Relative water content (%) of wheat as influenced by the application of potassium under different irrigation schedules.

Table 2. Relationship between water regimes and yield components of wheat.

Dependent variables	Independent variables	Water regimes	Regression equation	Correlation of coefficient (r)	Coefficient of determination (R^2)
Plant height	Grain yield	Normal irrigation	Y = 0.314 x – 32.625	0.966**	0.928
Plant height	Grain yield	Drought	Y = 0.216 x – 20.862	0.996**	0.991
Tillers m^{-2}	1000-grains weight	Normal irrigation	Y = 0.112 x + 8.280	0.986**	0.971
Tillers m^{-2}	1000-grains weight	Drought	Y = 0.243 x – 22.312	0.894**	0.800
Grains $spike^{-1}$	Grain yield	Normal irrigation	Y = 0.136 x – 3.846	0.987**	0.974
Grains $spike^{-1}$	Grain yield	Drought	Y = 0.150 x – 4.665	0.944**	0.891

Relative water content (RWC) was significantly affected by both water regimes. The RWC was 2.95% higher under normal irrigation than under water deficit (Fig. 3). Soil and foliar applications of different potassium treatments significantly affected leaf RWC. The maximum RWC (83.76%) was recorded when foliar application of 2% K was applied, followed by soil-applied potassium in recommended doses, where RWC was 83.32%. The lowest RWC (81.91%) was observed when potassium was not applied to soil in the form of a defensive shield.

Under water deficit conditions, the net photosynthetic rate was observed to be lower than that under normal irrigation. The net photosynthesis rate was 20.36% higher under normal irrigation than under water deficit (Fig. 4). The rate of net photosynthesis was influenced by the different potassium treatments. A higher net photosynthetic rate (6.90 µmol CO_2 m^{-2} sec^{-1}) was observed in the 2% foliar spray of potassium, whereas the lowest net photosynthetic rate (3.62 µmol CO_2 m^{-2} sec^{-1}) was observed in soil without potash application.

The stomatal conductance of wheat was less under drought conditions than under normal irrigation. Under water deficit conditions, stomatal conductance decreased by 17.61% compared to that under normal irrigation conditions (Fig. 5). Different potassium applications significantly influenced the stomatal conductance in wheat. Stomatal conductance was the highest (29.17 mmol H_2O m^{-2} sec^{-1}) in the treatment where potassium was used in the soil, similar to that observed for treatments with 1% and 2% foliar sprays of potassium.

The highest transpiration rate (0.80 mmol H_2O m^{-2} sec^{-1}) was observed with 2% foliar application of potassium. This finding is similar to that observed for 1% foliar spray of potassium, soil-applied potash, and distilled water spray. Minimum transpiration (0.59 mmol H_2O m^{-2} sec^{-1}) was noted in soil without potash application, and it was similar to that of treatments with distilled water spray and 1% potassium spray treatments (Fig. 6).

Potassium's Role in Improving Irrigation Water Use Efficiency in Wheat Exposed to Drought

Different potassium treatments significantly influenced irrigation water use efficiency in wheat (Fig. 7). Maximum irrigation water use efficiency (15.42 kg/ha/mm) was observed in plots where 2% potassium

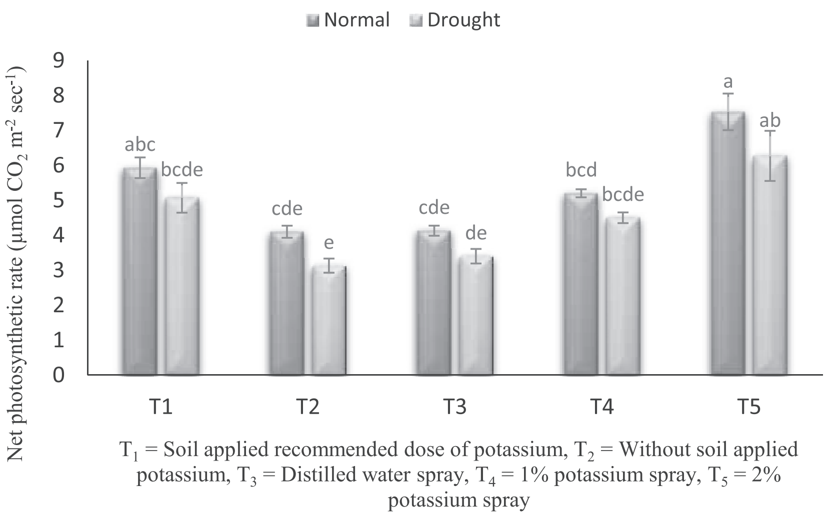
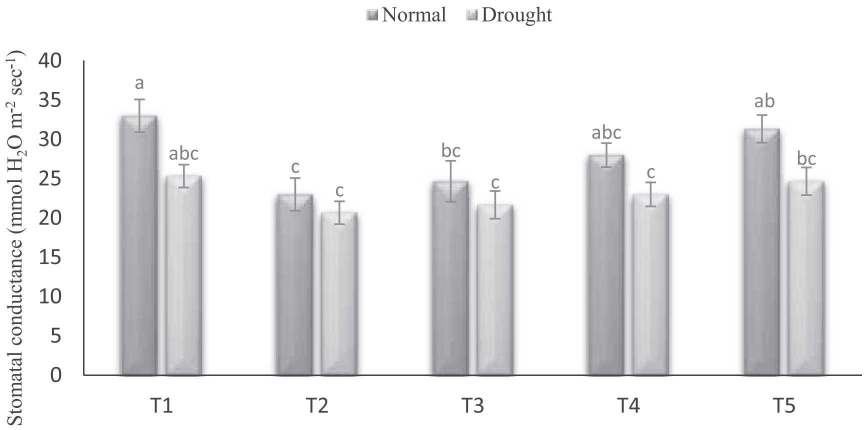
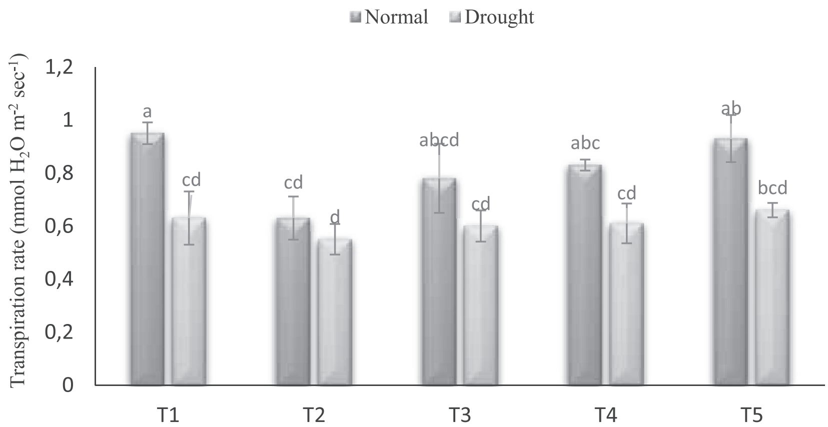


Fig. 4. Net photosynthetic rate (µmol CO_2 m^{-2} sec^{-1}) of wheat as influenced by the application of potassium under different irrigation schedules.



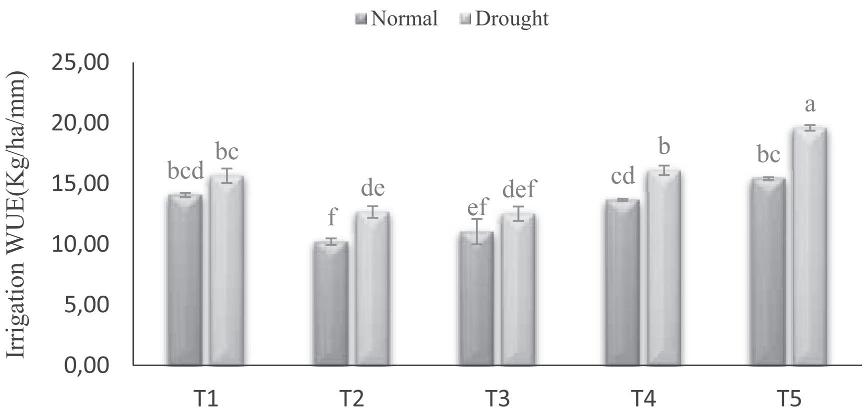
T_1 = Soil applied recommended dose of potassium, T_2 = Without soil applied potassium, T_3 = Distilled water spray, T_4 = 1% potassium spray, T_5 = 2% potassium spray

Fig. 5. Stomatal conductance (mmol H_2O m^{-2} sec^{-1}) of wheat as influenced by the application of potassium under different irrigation schedules.



T_1 = Soil applied recommended dose of potassium, T_2 = Without soil applied potassium, T_3 = Distilled water spray, T_4 = 1% potassium spray, T_5 = 2% potassium spray

Fig. 6. Transpiration (mmol H_2O m^{-2} sec^{-1}) of wheat as influenced by the application of potassium under different irrigation schedules.



T_1 = Soil applied recommended dose of potassium, T_2 = Without soil applied potassium, T_3 = Distilled water spray, T_4 = 1% potassium spray, T_5 = 2% potassium spray

Fig. 7. Irrigation WUE (Kg/ha/mm) of wheat as influenced by the application of potassium under different irrigation regimes.

spray was applied, whereas a minimum (10.21 kg/ha/mm) was observed in the absence of soil-applied potash.

Economic Analysis

Economic analysis revealed a positive effect of different potassium treatments in wheat exposed to drought at the tillering stage (GS-2 as per the Feekes scale) (Table 3). The variation in net return was observed due to different potassium treatments under normal irrigation and drought conditions. The maximum benefit-cost ratios were recorded at 1.24 and 1.30 due to 2% foliar application of potassium and soil-applied potassium, respectively, in wheat exposed to water deficit.

BCR = benefit-cost ratio, W_1 = normal irrigation, W_2 = drought, T_1 = soil-applied recommended dose of potassium, T_2 = without soil-applied potassium, T_3 = distilled water spray, T_4 = 1% potassium spray, and T_5 = 2% potassium spray.

Discussion

The present investigation regarding the impact of potassium nutrition on gas exchange characteristics, water relations, and water use efficiency of wheat exposed to water deficit at the tillering stage suggested that potassium nutrition, either as a foliar spray or soil application, is very effective for improving gas exchange characteristics, water relations, and water use efficiency of wheat, thereby increasing the grain yield of wheat under drought conditions. The present study showed that the shorter height of plants under drought conditions was due to a lesser availability of water, while an increase in plant height because of 2% potassium spray indicated optimum wheat growth [46] due to optimum soil moisture uptake. The application of readily soluble potassium to leaves improved the water relations and thus the growth of wheat, which affected the plant height of wheat [38]. The shorter plant height in maize exposed to drought was also reported by Abbasi et al. [47]. The poor water use in wheat may be linked to the condition in which potassium was not applied; thus, the number of tillers was recorded as lower. These results are in agreement with the findings reported by Ponkia et al. [48], who reported fewer tillers m^{-2} in plants where potassium was not applied. The translocation of assimilates from source to sink is greatly influenced by potassium spraying, which is the main cause of the increase in spike length [49]. The role of potassium in enhancing flowering and seed sets has been highlighted by Hasanuzzaman et al. [50]. Similarly, the superiority of foliar application over soil and no potassium application was observed in the current study, whereas more grains per spike and spikelets per spike were observed. Li et al. [51] also recorded more spikelets per spike in wheat because of foliar potassium application. The crucial role of potassium in improving water use efficiency [52] contributed to improving the partitioning of assimilates and translocation towards grains. Thus, potassium application did not increase grain $spike^{-1}$ of wheat. Similar results were reported by Yadav et al. [53]. For 1000-grain weight, despite the application of the recommended potassium dose to the soil, because of greater fixation of potassium in the soil, comparable results were achieved with foliar spray and 1 or 2% potassium. Saleem et al. [54] also reported a decrease in the 1000-grain weight of wheat when potassium was not applied. It can be concluded that the reduction in yield components because of the water deficit at tillering (GS-2 as per the Feekes scale) may be due to decreased photosynthetic surface area of leaves and, thus, reduction of photosynthetic efficiency. Zareian et al. [55] reported a link between the decrease in the photosynthetic efficiency of leaves and the water deficit in wheat. The crop productivity, or partitioning of assimilates in the economic parts of crops, is mainly dependent on the rate of photosynthesis. However, a higher uptake of potassium with rapid absorption also results in a greater yield benefit. Foliar application of K under drought conditions may have improved water relations in wheat, thus alleviating the harmful effects of water deficits and improving grain yield. These results agree with the findings reported by Naseem et al. [56], who stated that grain yield was reduced when potassium was not applied. Reduced straw yield under drought conditions may be due to reduced crop growth

Table 3. The benefit-cost ratio of wheat as influenced by the application of potassium under different water regimes.

Dependent variables	Independent variables	Water regimes	Regression equation	Correlation of coefficient (r)	Coefficient of determination (R^2)
Plant height	Grain yield	Normal irrigation	Y = 0.314 x – 32.625	0.966**	0.928
Plant height	Grain yield	Drought	Y = 0.216 x – 20.862	0.996**	0.991
Tillers m^{-2}	1000-grains weight	Normal irrigation	Y = 0.112 x + 8.280	0.986**	0.971
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Grains $spike^{-1}$	Grain yield	Normal irrigation	Y = 0.136 x – 3.846	0.987**	0.974
Grains $spike^{-1}$	Grain yield	Drought	Y = 0.150 x – 4.665	0.944**	0.891

and net assimilation due to limited water supply [47]. Improvement in straw yield is because of potassium application compared to plots where potassium was not applied, which may be because of a greater number of tillers per unit area. Arif et al. [46] also reported an improvement in the number of fertile tillers with the application of potassium as compared to those with no application of potassium. These results are similar to those reported by El-Abady et al. [57], who reported a decrease in straw yield in the absence of potassium.

The reduction in the relative water content and membrane stability index under drought conditions may be due to altered water relations. The stability of the cell membrane under drought conditions is an important mechanism for drought survival. The cell membrane stability index indicated the functionality of the plasma lemma and the normal functioning of cellular machinery. The production of more reactive oxygen species damages the integrity of the cell membrane, whereas potassium treatment enhances water uptake and retention, thus improving cell membrane stability in wheat.

Among the different gas exchange characteristics, adequate potassium supply improves the assimilation of photosynthate. Damage to the chloroplast structure under drought conditions due to the production of more reactive oxygen species [58, 59] may be the main reason for the reduction in net photosynthesis. Application of an adequate quantity of potassium resulted in an improvement in the transportation of photo-assimilates from leaves to roots, thus positively influencing photosynthesis [60]. Cai et al. reported a decrease in the net photosynthetic rate of potassium-deficient maize [61]. However, similar chlorophyll contents with soil and foliar application of potassium may be because soil application resulted in the fixation of a considerable quantity of potassium, while the consumption of potassium from the rest of the available dose was not shown in terms of an increase in chlorophyll content.

Improvement in stomatal conductance and transpiration rate due to potassium fertilization under drought may be due to the pumping of potassium from guard cells, thus closing the stomata tightly and resulting in the conservation of water. A decrease in the stomatal conductance in sunflowers where potassium was not applied under drought conditions was also recorded by Hussain et al. [31]. A higher transpiration rate is an indication of a reduction in the harmful effects of water deficit in wheat due to the influence of potassium. The optimum supply of potassium might have improved the uptake of nutrients by enhancing the transpiration rate and, thus, the mass flow of soil solution to the root surface, which repaired the damaged tissues due to oxidative stress under drought. Similar results were documented by Zareian and Tabatabaei [55], who reported that transpiration decreased in wheat where potassium was not used.

The increase in irrigation water use efficiency with foliar application of potassium may be because of the significant role of potassium in water relations to plants. These results suggested an important role for potassium as an osmo-protectant under drought stress. Abbasi et al. [47] also highlighted the importance of osmo-protectants in conferring drought tolerance by improving water-use efficiency in maize. AlKhader et al. [62] also reported higher irrigation water use efficiency in watermelons in which potassium was applied.

Conclusions

According to the present study, foliar- and soil-applied potassium improved different agronomic and yield-related traits of wheat under drought conditions compared to that of the control. However, the benefit-cost ratio was greatly improved for both soil-applied potassium and 2% foliar-applied potassium as compared to that of the control under drought conditions. However, maximum improvement in grain yield and irrigation water use efficiency was observed with 2% foliar-applied potassium under drought at tillering. Therefore, a foliar spray of 2% potassium can be advantageous in comparison to a 1% potassium foliar spray or no potassium under water deficit at tillering in wheat. However, considering the benefit-cost ratio, soil with applied potassium and 2% foliar spray can be effectively utilized to reduce the harmful effects of water deficit at tillering in wheat.

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Conflict of Interest

The author declares no conflict of interest.

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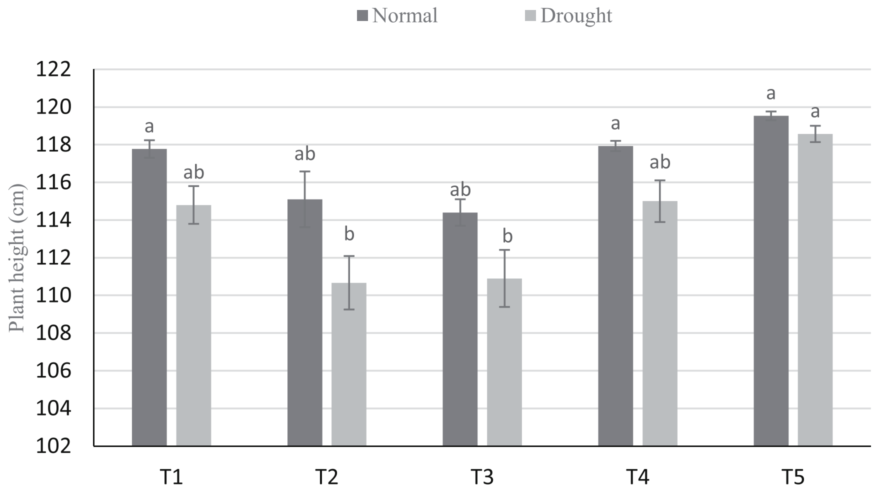
Supplementary Data



T_1 = Soil applied recommended dose of potassium, T_2 = Without soil applied potassium, T_3 = Distilled water spray, T_4 = 1% potassium spray, T_5 = 2% potassium spray

Fig. S1. Plant height (cm) of wheat as influenced by the application of potassium under different irrigation regimes.

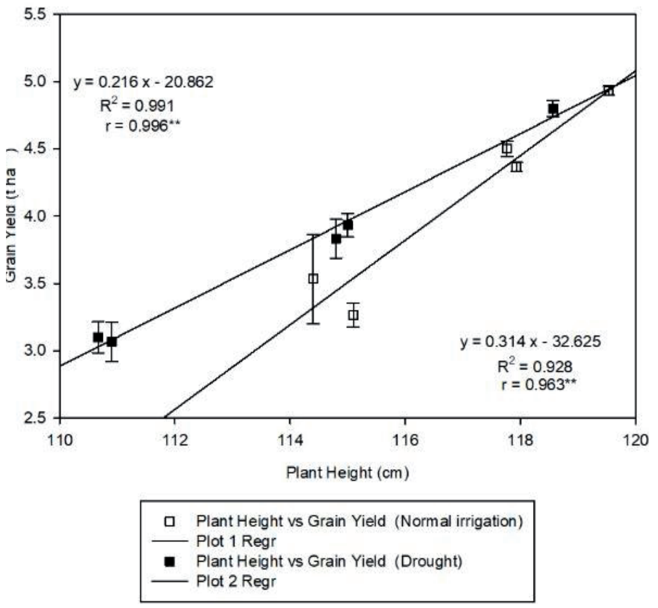


Fig. S2. Relationship between plant height and grain yield of wheat under normal irrigation and drought.

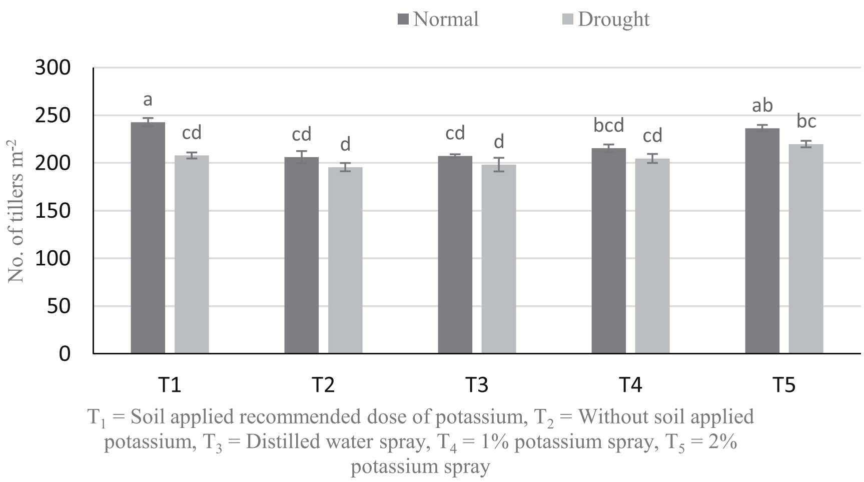


Fig. S3. Number of Tillers m^{-2} of wheat as influenced by the application of potassium under different irrigation regimes.

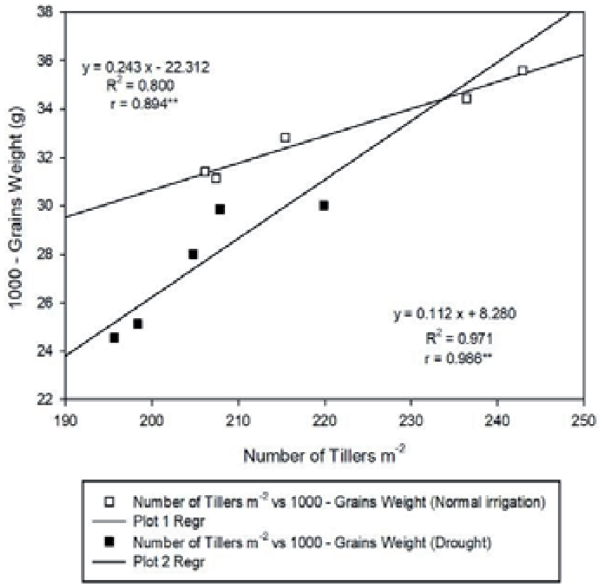


Fig. S4. Relationship between number of tillers m^{-2} and 1000- grains weight of wheat under normal irrigation and drought at tillering.

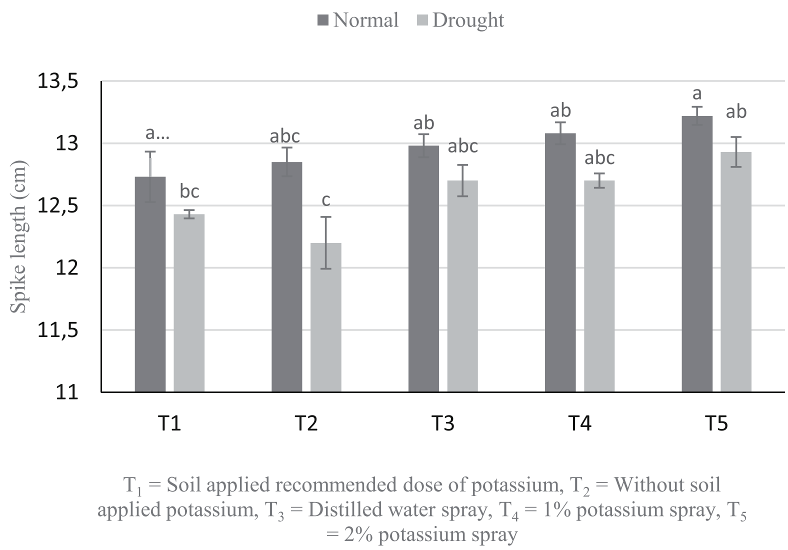


Fig. S5. Spike length (cm) of wheat as influenced by the application of potassium under different irrigation regimes.

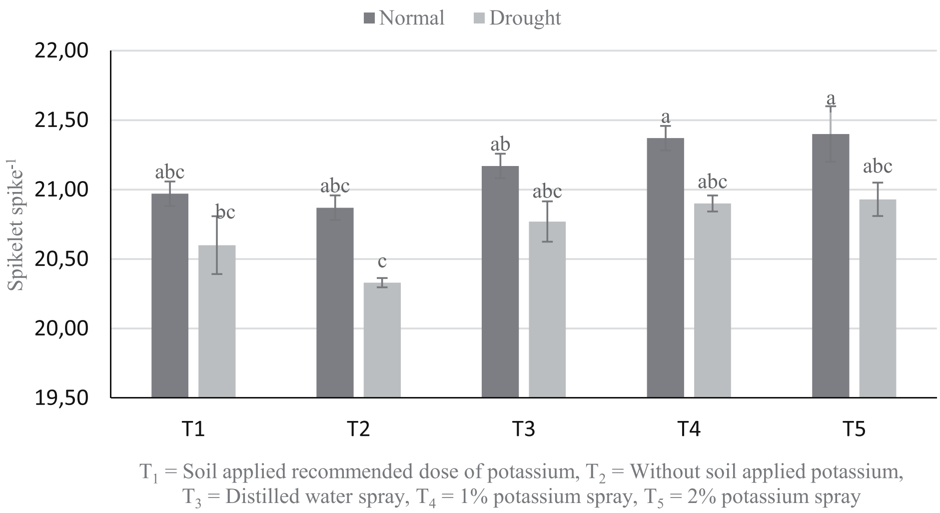


Fig. S6. Spikelet spike^{-1} of wheat as influenced by the application of potassium under different irrigation regimes.

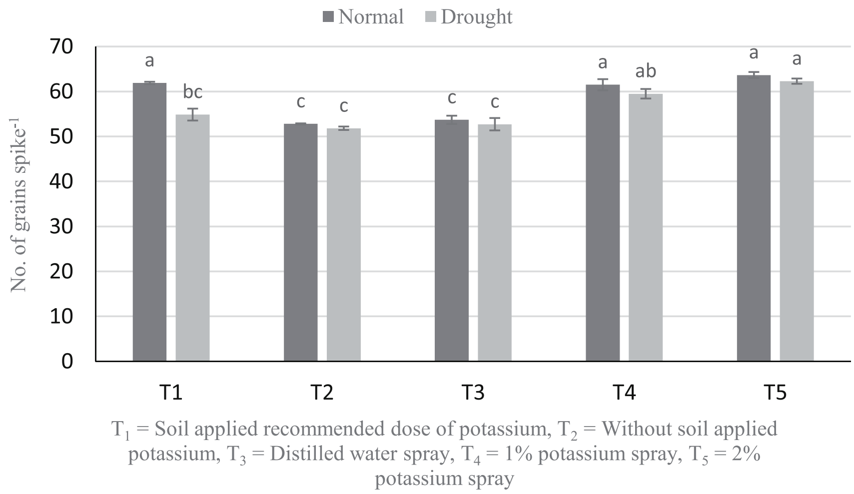


Fig. S7. Number of grains spike^{-1} of wheat as influenced by the application of potassium under different irrigation regimes.

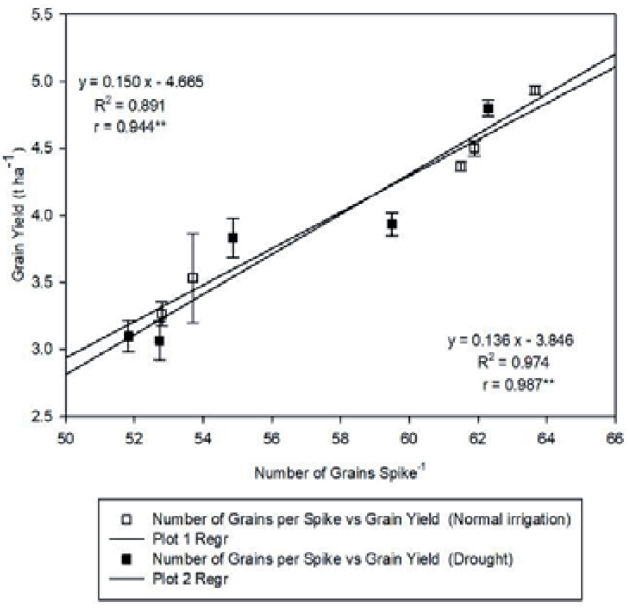


Fig. S8. Relationship between the number of grains per spike and grain yield of wheat under normal irrigation and drought at tillering.

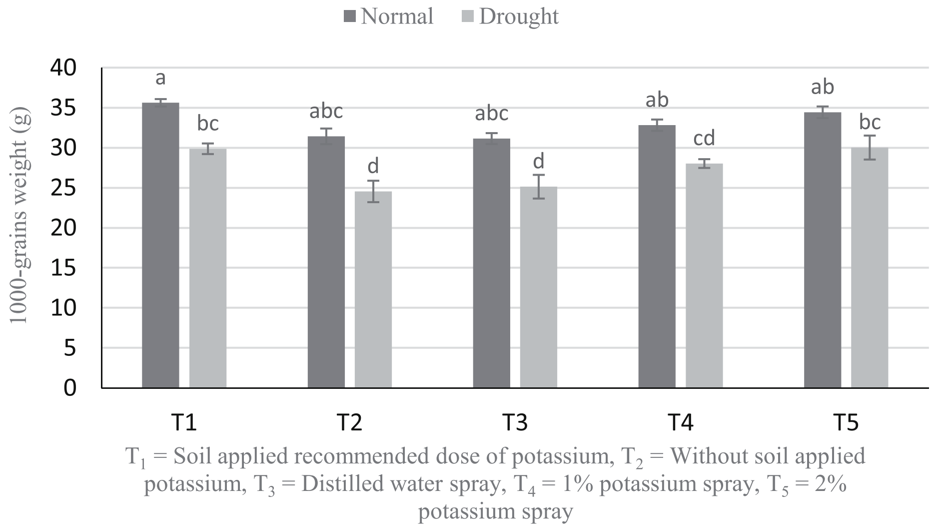


Fig. S9. Thousand grains weight (g) of wheat as influenced by the application of potassium under different irrigation regimes.

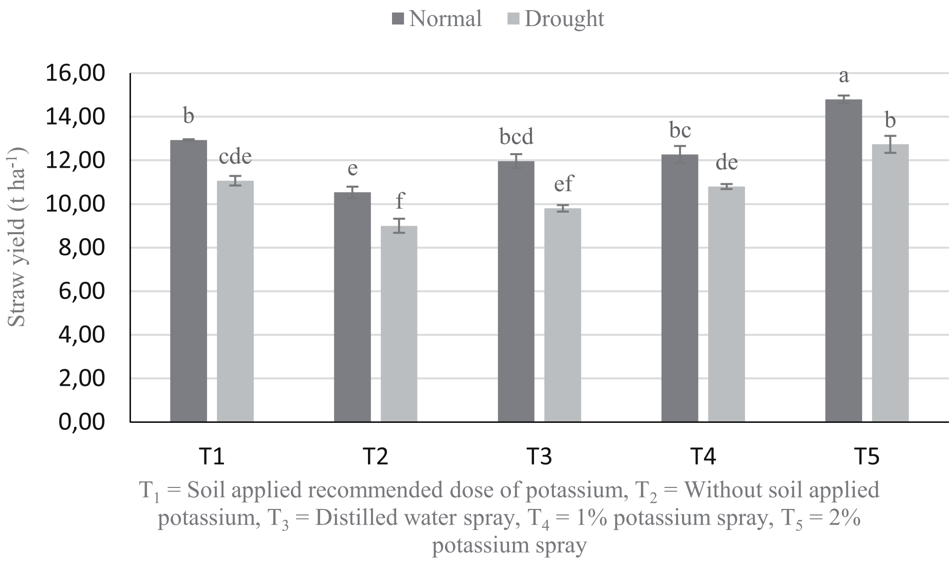


Fig. S10. Straw yield (t ha-[1]) of wheat as influenced by the application of potassium under different irrigation schedule.

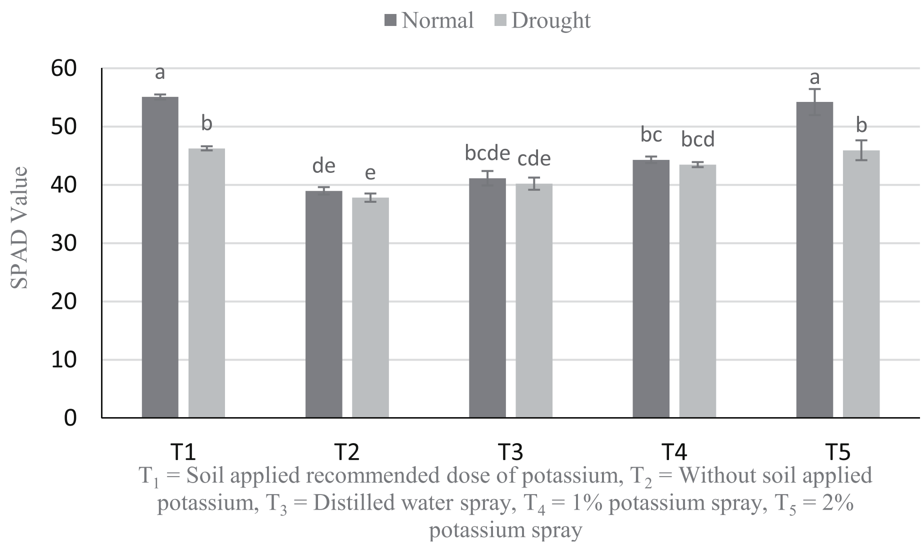
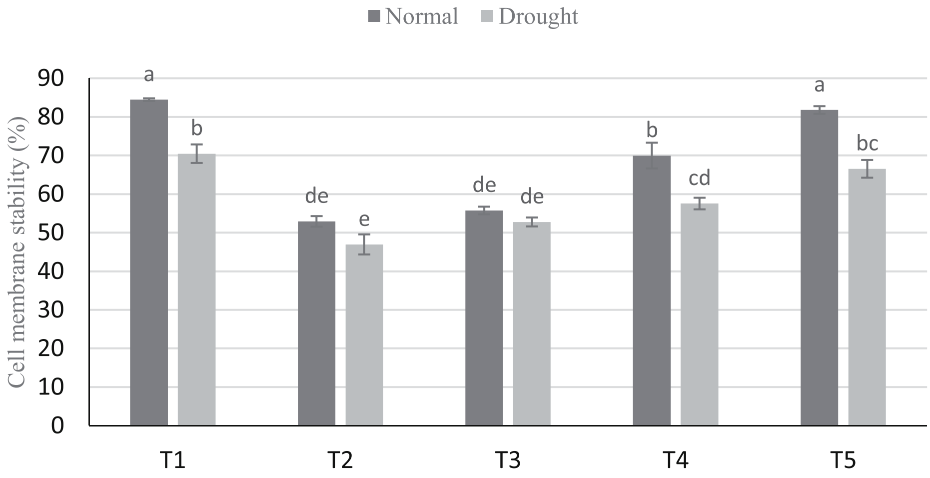


Fig. S11. Chlorophyll content of wheat as influenced by the application of potassium under different irrigation schedule.



T_1 = Soil applied recommended dose of potassium, T_2 = Without soil applied potassium, T_3 = Distilled water spray, T_4 = 1% potassium spray, T_5 = 2% potassium spray

Fig. S12. Cell membrane stability index of wheat as influenced by the application of potassium under different irrigation schedules.